Renewable and Sustainable Energy Reviews 37 (2014) 435–459

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis

Mateus Henrique Rocha [a,*], Rafael Silva Capaz [b], Electo Eduardo Silva Lora [a], Luiz Augusto Horta Nogueira [b], Marcio Montagnana Vicente Leme [a], Maria Luiza Grillo Renó [a], Oscar Almazán del Olmo [c]

[a] *NEST – Excellence Group in Thermal Power and Distributed Generation, Institute of Mechanical Engineering, Federal University of Itajubá, Av. BPS 1303, Itajubá, Minas Gerais State, CEP: 37500-903, Brazil*

[b] *IRN – Institute of Natural Resources, Federal University of Itajubá, Av. BPS 1303, Itajubá, Minas Gerais State, CEP: 37500-903, Brazil*

[c] *ICIDCA – Instituto Cubano de Investigaciones de los Derivados de la Caña de Azúcar, Via Blanca y Carretera Central 804, San Miguel Del Padrón, A.P. 4036, La Habana, Cuba*

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form
16 April 2014
Accepted 11 May 2014
Available online 3 June 2014

Keywords:
Life cycle assessment (LCA)
Ethanol
Biodiesel
Sugarcane
Soybean/Palm oil
Net energy ratio (NER)

ABSTRACT

The key objective of this study is to evaluate and compare the main environmental life cycle impacts and energy balance of ethanol from sugarcane and biodiesel from soybean and palm oil, in the Brazilian conditions. The methodological tool used was the Life Cycle Assessment (LCA), in Well-To-Tank (WTT) perspective. A process based on cradle-to-gate attribution LCA method, was applied as the technique to assess the health and environmental impacts of ethanol and biodiesel production systems. The environmental assessment was carried out using the SimaPro 7.0.1 software and the CML 2 baseline 2000 methodology, developed by the Institute of Environmental Sciences (CML). The assumed common analysis base in this paper was 1.0 MJ of energy released by combustion of the analyzed biofuels. The environmental impacts were quantified and ranked in categories of impacts: Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Acidification Potential (ACP) and Eutrophication Potential (ETP). In addition, the results were compared by meta-analysis with previous published studies. The Net Energy Relation (NER) in the life cycle of biofuels is an important indicator of the technical and environmental performance evaluation of biofuels production. In this study the NER of ethanol and biodiesel from soybean and palm oil were estimated and compared with previous published studies. Direct and embodied energy inputs, based on defined system boundaries, were used to estimate the energy requirement of crops production, juice/oil extraction, and ethanol/biodiesel industrial production. It is possible to conclude, that biofuel production systems with higher agricultural yields and extensive use of co-products in its life cycle present best environmental results. The analysis of obtained results shows that the choices of co-products allocation method, transport distance and inventory database of the country, have significant influence on the results of the life cycle environmental performance of biofuels.

Contents

* Corresponding author.
E-mail addresses: mateus0@yahoo.com.br (M.H. Rocha), electo@unifei.edu.br (E.E.S. Lora).

http://dx.doi.org/10.1016/j.rser.2014.05.036
1364-0321/

1. Introduction

Currently, the quest for alternatives scenarios to fossil fuels can be observed in the transport sector, supplied mostly with petroleum-based products, responsible for 19% of the global consumption of energy and for 25% of CO_2 emissions [1]. The use biofuels has stronger expansion in relation to other alternatives, such as, fuel cells, natural gas and electric vehicles. The main driving forces of biofuels production seems to be the renewability of this resources, the energy security provided by diversified supply, the climate change mitigation, and the creation of new alternatives for agriculture, also including the appeal of new jobs [2–6].

It is well known that biofuels are defined as fuels produced from biological resources, synthesized directly or indirectly through photosynthesis. Biofuels are derived from crops, such as, corn, soybeans, sugarcane, sugar beets, wheat, barley, cassava (first generation biofuels) or agricultural lignocellulosic biomass, which are either non-edible residues of food crop production or non-edible whole plant biomass (second generation biofuels) [7–10].

The liquid biofuels that are largely produced and consumed are biodiesel and ethanol, which substitute fossil diesel and gasoline, respectively. They can be produced through chemical conversion (acid hydrolysis, transesterification/esterification, supercritic fluid extraction, aqueous phase reforming), biological conversion (fermentation, anaerobic digestion, enzymatic hydrolysis, photochemical conversion), thermochemical conversion (combustion, gasification, pyrolysis, liquefaction), or simply by mechanicals ways (comminution, pelletizing, etc.) [11–17].

Over the last ten years biofuels production worldwide has increased dramatically. With regards to ethanol, the production is concentrated mainly in the USA and Brazil. It is estimated that these two countries accounted for about 80% of the whole world production as recorded in 2009 and it is expected to reach 100 billion liters in 2015. Between 2000 and 2009 fuel ethanol output experienced an increase from 16.9 to 72.0 billion liters [18–21].

In Brazil the ethanol production reached 27.5 billion liters in 2009 and 2010/2011 harvest was estimated to reach almost 30.0 billion liters. Brazil produces more than 30% of the world's ethanol, being its production concentrated in the Center-South region, especially in the São Paulo State, which accounts for 59% of the national production. About 80% of the production is consumed domestically, where ethanol currently replaces 40–45% of the gasoline. Brazil's national market growth, forces this sector to offer solutions to land use and sustainability issues, to be able to maintain investments and its leadership [20–24].

With regards to biodiesel, between 2000 and 2009 the production experienced increase from 0.8 to 14.7 billion liters, this production is distributed in Germany (48% of total), other European countries (30%), USA (15%) and several other countries, such as Brazil, China, India, Canada, Colombia, Indonesia, and Malaysia, the remaining. The EU is the world leader in biodiesel production (with 78% of the world total) and consumption of biodiesel. By 2020, the USA is expected to become the world's largest single biodiesel market, will account for roughly 18% of world biodiesel consumption with 2.1 billion liters in 2009 [25–31].

In 2010 in Brazil, 23.0 million hectares of crop land were used for soybean production, 13.0 million hectares for corn and 9.0 million hectares for sugarcane. The remaining 23.0 million hectares are used for other minor crops. The Brazilian National Program on Biodiesel Production and Usage (PNPB) started in 2005. The PNPB established an increase of the blending to 5% from 2013 onwards, in July 2009, the Brazilian government already mandated a 4% biodiesel blending share it is possible that the 5% biodiesel target will occur before 2014. Brazilian biodiesel production is mostly based on soybean, though other important vegetable oil sources are castor bean, palm tree, tallow and jatropha [20–23,32–35].

The expanding biofuels global market has raised concerns about its sustainability. Certain basic and recurrent issues are the potential impact of biofuels on food security and agricultural commodity prices as well as social and environmental impacts as deforestation, monoculture, water resource depletion, and labor conditions. These concerns pose challenges to the development of the biofuel market and require further analysis and discussion. Life Cycle Assessment (LCA) methodologies are considered as the analysis model to determine quantitatively the environmental impacts comparison of the different types of biofuels production [10,18,36–40].

The key objective of this paper is to carry out an evaluation of the main environmental impacts and energy balance of the ethanol and biodiesel production systems in the Brazilian conditions, using the LCA methodology. The results are compared through a meta-analysis with previous studies published in the

Nomenclature

EC	energy content
HV	heat value
LHV	low heating value
NEB	net energy balance
NER	net energy ratio
NEY	net energy yield
PE	primary energy
S	area
V	volume
Yr	year

literature. The types of the impacts that were studied in the Life Cycle Impact Assessment (LCIA) include Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), Acidification Potential (ACP) and Eutrophication Potential (ETP). A process based on the cradle-to-gate attributional LCA method was applied, as the technique to assess the health and environmental impacts of ethanol and biodiesel production systems. The Life Cycle Inventory (LCI) data collection for each scenario of ethanol and biodiesel production was outlined based on the goal and scope of the study. The required inventory data were collected from published available inventory databases. The energy balance was carried out by the output/input energy relation that is proposed as an indicator. This allows to show how many units of renewable energy are obtained, when one unit of fossil energy is consumed.

2. General background

2.1. Ethanol

The parameters associated to the crop as agricultural yield and concentration of polysaccharides can indicate a potential viability to use some species in the production of biofuel. Crops such as sugarcane, wheat and corn are the most essential types of natural bioresources that are used for ethanol production (Table 1). Compared with corn based or sugar beet-based ethanol, Brazil's sugarcane-based ethanol have considerably more favorable results in terms of energy balance and reductions in Greenhouse Gases (GHG) emissions. Feedstock containing significant amounts of sugar or materials that can be converted into sugars, such as starch or cellulose, can be used in the production of ethanol [40–43].

In Brazil, the sugarcane crop yield ranges from 80.0 to 85.0 t of sugarcane per hectare (tc/ha); it is expected an increase of low tillage practices and the most important changes may happen in the cane harvesting, which will move from burned cane manual harvesting to mechanical harvesting of unburned cane. As a consequence, great amounts of straw (sugarcane trash) will be available, and its use as energy source is already becoming an attractive option for mills, although the route for sugarcane trash recovery (harvest and transportation) is still not well established [45–48].

Currently, the industrial efficiency (sugar recovery) is around 90%. The generation and use of co-products in the process of biofuels production grants good indicators in energetic, economic and environmental terms. For sugar and ethanol production from sugarcane the main co-products are bagasse, stillage, filter cake and residual boiler ashes. The bagasse obtained averages 250.0–290.0 kg/tc, with 50% moisture content, this ensures energy self-sufficiency to the Brazilian mills and still provides surplus of electricity to the grid, using a CHP systems, usually based on steam cycles [49–52].

The operation of a sugar and alcohol mill in a typical Center-South Brazil conditions, with a crushing capacities of 2.0 million tc/year, conventional cogeneration systems at 6.5 MPa and 480 °C corresponds to an installed capacity of 31.0 MW_e, while for systems optimized at 9.0 MPa and 520 °C, the power output could be 82 MW_e, during the harvest operation. In addition, the sugar and alcohol sector has great potential for increasing overall production efficiency by repowering improvements in mills' cogeneration plants, electrification of the drives of the preparing and extraction plants, sugarcane bagasse hydrolysis for second generation ethanol production, sugarcane bagasse gasification for syngas production and subsequent utilization in advanced cogeneration systems [53–56].

The environmental advantages of sugarcane based ethanol as fuel are focusing in gasoline substitution and GHG emissions avoidance in the whole life cycle. The total emissions avoided (including indirect emissions), when the energy surplus of the co-products is used to replace the considered fuel oil, can reach 12.5 kg CO_2/tc (in an average scenario) and 23.3 kg CO_2/tc (in modern technologies available). The use of sugarcane trash as a source of fuel in addition to the bagasse could increase, by more than 50%, the generation of surplus electricity [45,50,57–59].

The filter cake and the stillage can be used in the sugarcane plantation as fertilizer, due to the convenient concentration of nitrogen, phosphorus and mainly potassium in their composition. Known since the 60s, the application of this residue on the sugarcane plantation has intensified since 1979, influenced by environmental issues and the high cost of fertilizers. Rocha et al. [60] and Rocha et al. [61] presented a mass and energy balance of stillage treatment and disposal, showing a fertilizer mass savings of 100% for the potassium, 35% for nitrogen and 20% for phosphorus in the manure, when stillage is applied to 40% of the area of plant and ratoon. The sugarcane ethanol industry is undergoing a huge technological changes that could be defined as new paradigms. A detailed description of this trends is included in Lora et al. [62] and Lora et al. [63].

Table 1
Agricultural crops used to ethanol production and their yield [44].

Crop		Average agricultural yield (ton/ha)	Average biofuel yield (L/ha)
Barley	*H. vulgare*	2.81	1050
Wheat	*Triticum*	3.01	2450
Corn	*Zea mays L.*	5.16	3050
Sugar beet	*Beta vulgaris*	53.15	5000
Sugar cane	*Saccharum L.*	69.86	6000

2.2. Biodiesel

In biodiesel production of African palm oil vegetable oil could be more interesting than others conventional feedstocks, like soybean and rapeseed ones (Table 2). In 2010, the production of palm oil and palm kernel oil corresponded to 37% of the global production of vegetable oil and soybean oil (28%). USA and Brazil are responsible for 60% of the production of soybean in the world. In 2010, Brazil produced 69.0 million tons of soybeans, from which 6.5 million tons of oil were extracted and 26.1 million tones of meal produced. Malaysia and Indonesia are responsible for more than 80% of the world production of palm oil [4,10,64–66].

Soybean oil was the primary feedstock used for biodiesel production worldwide. The production technology is divided into five stages: (1) soybean production (or farm outputs), (2) transport of soybeans to the processing facility, (3) separation of oil and meal, (4) conversion into biodiesel (or transesterification), and (5) transportation of biodiesel for distribution. In the soybean industry the most important product is the meal, which corresponds approximately to 80% w/w of the grain, used as human and animal protein source. The oil is destined to the food and cosmetic industry and the shells, produced in low amounts, can be used as animal feed too [67–70].

The palm trees are planted at a density of 136–160 trees/ha. The palm oil mill produces Crude Palm Oil (CPO) and palm kernels. Palm oil tree is the only crop that produces two types of oils from its fruit: palm oil from the mesocarp and kernel oil from the kernel. Palm oil fruits are clustered together in bunches commonly called Fresh Fruit Bunches (FFB), weighing 10–20 kg and each carrying 1000–3000 fruits. Each oil palm tree can produce 10–15 brunches of FFB per year, which corresponds to 18–20 t of FFB/ha/year [66,71–74].

The harvested FFB contain around 20% oil, 27% nuts, 5% kernels, 14% fiber and 8% shell and 23% Empty Fruit Bunches (EFB). The palm oil mill could obtain energy from a cogeneration system by using part of the EFB, the Palm Kernel Shells (PKS) and the Palm Press Fiber (PPF) as fuel. The Palm Oil Mill Effluent (POME) is treated in simple biological pond system called lagoons and used for irrigating the plantations. The POME can also be treated in anaerobic digesters to produce biogas; at a range of 14 m^3 of biogas/ton FFB, which contains 65% CH_4 and 30% CO_2 by volume. It is estimated that more than 90% of the electricity consumption of the mills could be produced from theses co-products, which also explains the favorable energetic balance and environmental performance of this chain of biodiesel production [75–79].

Different methods to evaluate the use of waste cooking oil to biodiesel production have been analyzed with their possible variations (alkaline catalysis, acid catalysis, enzymatic catalysis and non-catalytic conversion techniques) [80].

Table 2
Agricultural crops used for biodiesel production and their yields [44].

Crop		Average agricultural yield (ton/ha)	Average biofuel yield (L/ha)
Soybean	*Glycine max*	2.24	550
Castor	*Ricinus comunis*	1.00	700
Sunflower	*Heliantus annus*	1.37	950
Rapeseed	*Brassica napus*	1.98	1200
Jatropha	*Jatropha curcas*	4.00	2800
Palm	*Elaeis guineensis*	14.10	4500

2.3. Life cycle assessment

In regards to the environmental impacts of biofuels, the LCA methodology represents an important tool, used to estimate the positive or negative impacts, in all the stages of the biofuels life cycle. This tool was standardized by the International Standard Organization (ISO), who defined its guidelines, it is used as a tool to measure biofuels benefits and to select the most convenient alternative from different points of view [81,82]. More recently, LCA had adopted it not only for qualitative assessments, but also to provide a quantitative absolute assessment of the environmental balance of biofuel chains [83].

The LCIA is a stage of LCA can be expressed as a quantitative and/or qualitative process to characterize and assess the effects of the environmental interventions identified in the LCI, containing as the main issues: category definition, classification, characterization and valuation/weighting. The impact categories are selected in order to describe the impacts caused by the products or by the product systems. A second element included in the LCIA is the impacts classification, which is a qualitative step based on scientific analysis of relevant environmental processes [84–87].

However, the results of LCA studies strongly depend on the information given as input, regarding the geographic and inventories used, and others premises like the boundaries of the analyzed system and the allocation method. Because of this, different LCA results for the same product are meet easily, disclosing the absence of a consolidated standard, that does not always allows the direct comparison of the studied alternatives, causing the diversity of interpretations [88–91].

A meta-analysis of several published LCA, as it will be done thereof ethanol and biodiesel energy systems will provide a better understanding of the environmental implications of deploying the biofuels considered in this paper. However, this paper intends to carry out a comparison of the range of LCA results from some published papers, rather than to develop a consistent statistical method for comparing management methods and then to adjust each LCA's results to fit the ISO standardized methodology. The meta-analysis was well discussed by Nelson and Kennedy [92].

3. Methodology

3.1. Goal and scope of this study

The goal and scope of this paper is to carry out an evaluation of the main environmental impacts and the energy balance of the ethanol production from sugarcane and biodiesel production from soybean and palm oil under the Brazilian conditions, using the LCA methodology. A process based on the cradle-to-gate attribution LCA method was applied and the results are compared through a meta-analysis to previous published studies (Table 3). The types of impacts studied in

Table 3
Previously published works that will be compared in this paper.

Biofuel	Reference	Country	LCA environmental impacts	LCEA (energy balance)
Ethanol – sugarcane	Capaz [93] – Base case	Brazil	No	Yes
	Macedo et al. [94]	Brazil	GHG emissions	Yes
Biodiesel – Soybean oil	Capaz [43] – Base case	Brazil	No	Yes
	Cavalett and Ortega [95]	Brazil	Emergy Analysis and Embodied Energy Analysis	Yes
	Tsoutsos et al. [96]	Greece	Yes	No
	Pradhan et al. [97]	USA	No	Yes
	Carraretto et al. [98]	Italy	Yes	Yes
Biodiesel – Palm oil	Costa [99] – Base case	Brazil	Yes	Yes
	Kamahara et al. [100]	Indonesia	No	Yes
	Papong et al. [101]	Thailand	No	Yes
	Souza et al. [102]	Brazil	GHG emissions	Yes
	Pleanjai and Gheewala [103]	Thailand	No	Yes

LCIA included: ADP, GWP, HTP, ACP and ETP. This systematic approach eventually reveals the potential of the product evaluated and identify the environmental hot spots in the product chains so that precautionary steps can be suggested to reduce the negative environmental impact.

The Life Cycle Energy Assessment (LCEA) is a method based on accounting the energy flows throughout the life cycle of products. The energy balance is carried out using the output/input energy relation that is proposed as an indicator. This allows to show how many units of renewable energy are obtained when one unit of fossil energy is consumed.

3.2. Life cycle inventory background dates

LCI background data include inputs and outputs in processes for the production of accessory materials and process energies, as well as the direct emissions, such as, the production of steam, electricity, fertilizers, diesel, pesticides, and chemicals. Background data are normally incorporated in international databases, but sometimes the processes conditions (e.g. energy structure, energy efficiency, emissions, etc.) are different. This background data were sourced from the Brazilian (in most cases) and international databases (when could not find suitable data to Brazilian conditions).

In these cases, the data was compiled from studies on the background processes as follows: diesel fuel [104], nitrogen (urea) [105], phosphorus (P_2O_5) [106], potassium (K_2O) [106], herbicide [106], insecticide [106], lime [106], lubricant [104], electricity [107], gasoline [104], propane [105], natural gas [105], hexane [105], crude oil [104], methane [105], sodium hydroxide [106], sodium methoxide [106], methanol [108], phosphoric acid [109], hydrogen chloride [110], magnesium [111], sulfuric acid [106], crude oil [104], fuel oil [104], bentonite [111], diesel emissions [112], natural gas emissions [112], crude oil emissions [112], gasoline emissions [112], fuel oil emissions [112], propane emissions [112], methane emissions [112] and boron [110].

3.3. Life cycle impact assessment

The LCIA was carried out based on the inventory analysis data generated for the unit processes. The inventory data was classified according to its potential impact on the environment. The LCIA includes emissions to air, soil and water and was used to improve the understanding of the results of the LCI phase. The method applied in this work was the CML 2 Baseline 2000 method that is an update from the CML 1992 method [113]. This method has been developed and published by the Institute of Environmental Sciences (CML) of the Leiden University. Most of the impact categories have a global geographic scope. Some of them have scopes varying between local, regional, continental and global scales. Grouping and weighting, as optional steps, were not included in the CML 2 method.

The software package SimaPro 7.0.1 (Pré Consultants, The Netherlands) had been chosen because it is a widely used LCA tool, both by professionals and researchers. The impact categories were chosen as to cover a maximum of environmental/human health effects. The following midpoint impact categories used to carry out the environmental impacts assessment were conducted through five categories [113]:

- ADP: that represents the natural resources depletion such as iron ore, crude oil, which are regarded as non-renewable, is expressed in kg of Antimony equivalents (kg Sb-eq.).
- GWP: which is related with emission of CO_2, CH_4 and N_2O, is expressed in kg of Carbon Dioxide equivalents (kg CO_2-eq.).
- HTP: which extends to the number of chemicals covered and distinguishes between cancer and non-cancer effects, expressed as kg of 1,4-Dichlorobenzene equivalents (kg 1,4 DB-eq.).
- ACP: is defined as the loss of base nutrients (calcium, magnesium and potassium) through the process of leaching and their replacement by acid elements (hydrogen and aluminum). This impact is associated with atmospheric pollution arising derived sulfur (S) and nitrogen (N) as NO_x or NH_3, is expressed in kg of Sulfur Dioxide equivalents (kg SO_2-eq.).
- ETP: is considered a process whereby water bodies, such as lakes, estuaries or slow-moving streams receive excess nutrients that stimulate excessive plant growth. Nutrients can come from many sources, such as fertilizers, deposition of nitrogen, erosion of soil containing nutrients, etc., is expressed in kg of Phosphate equivalents (kg PO_4^{-3}-eq.).

3.4. Life cycle energy assessment

The LCEA is a method used to quantify total energy flow and assess the overall efficiency of processes, in such a way that various net energy metrics or energy indicators can be estimated [65,66–70,73,85].

According to Fore et al. [114], there are several indicators commonly used in the literature to summarize the net energy produced from a particular system, as Net Energy Balance (NEB), that is the output energy minus the input energy measured, Net Energy Yield (NEY) that is the output energy minus the input energy calculated on a feedstock production area basis measured in MJ/ha and the Net Energy Ratio (NER), that is the output energy divided by the input energy. The relevance of the different net energy metrics depends on part on the question or objective being addressed (Table 4).

In this study, the LCEA was conducted considering the same boundaries and inputs, defined to LCA just for biofuels. The energy flows were assessed using NER indicators, The NER_{total} considered the output of biofuels and the others co-products evaluated by their Low Heating Value (LHV). The $NER_{biofuel}$ considered only the output of biofuel; and finally the $NER_{allocated}$ considered the output of biofuel with allocation by mass. When the consulted study did not present the coefficient used, the highest coefficient used in the others studies was adopted.

3.5. Ethanol

3.5.1. Functional unit

In LCA, the Functional Unit (FU) provides a reference to which the inputs and outputs are related. If the environmental impacts of the crops under study are compared, then a common base for comparison must be identified before defining the FU, ensuring that the choice of FU stands in close relation to the goal and scope of the study. The common base assumed in this study is 1 MJ of energy released by the combustion of ethanol, based on its LHV that is 28.0 $MJ/kg_{ethanol}$.

Table 4
Equations used for calculating energy balances indicators of biofuels.

Number	LCEA method	Equation	Reference
1	NEB	$NEB = \frac{(HV_{Biofuel} + \sum EC_{Co-products}) - (\sum PE_{Inputs})}{V_{Biofuel}}$	Mourad and Walter [65]
2	NEY	$NEY = \frac{\sum HV_{Biofuel} - \sum PE_{Fossil\ \ Fuel}}{S \cdot Yr}$	Kaltschmitt et al. [115]
3	NER	$NER = \frac{HV_{Biofuel} + EC_{Co-products}}{\sum PE_{Inputs}}$	Kamahara et al. [100]

3.5.2. Life cycle boundaries

The boundary of biofuels production systems included the agricultural and industrial processes stages, considering the transport between them. The input associated to constructions facilities, i.e. manufacturing, machines, buildings, vehicles, etc., were excluded from the inventories presented in the studies. Generally, it was estimated that the contribution of capital goods in agricultural products and industrial process, varies between 2% and 6% of environmental charges and lower than 10% of energy input [116].

In the life cycle of ethanol production (Fig. 1) the agricultural stage is fully integrated to the industrial production. In the agricultural system boundary of ethanol production the use of fuels, fertilizers, herbicides, insecticides, lime and seeds is considered. It is common to use stillage and other ethanol industry co-products (filter cake and ashes) as a complement of chemical fertilizers. The industrial step includes sugarcane milling, juice clarification and treatment, fermentation, distillation and purification of ethanol. The mills produce electricity by burning sugarcane bagasse in boilers furnace to generate steam, which in turn is used to drive steam turbines generators for electricity production in cogeneration plants. In the boundary of industrial system of ethanol production the use of NaOH, lime, H_2SO_4, C_6H_{12} and lubricants is considered [117–120].

3.5.3. Life cycle inventory

The analysis of ethanol production from sugarcane performed on the base of a case study evaluated by Capaz [93], was based on data supplied by regional research for the year 2007/2008 harvest. The ethanol plant has a capacity of 120,000 L/day, operating 180 days per crop. Two scenarios for analysis were defined, considering or not the application of filter cake and stillage for sugarcane fertilization. In addition to the conventional fertilization, it is considered to use filter cake and stillage 30% (for plant cane areas) and 35% (for ratoon areas). Sugarcane is planted using cane stools (plant cane), it is cut and grown again (ratoon cane) four times (years), before replanting.

Fertilizers ($N–P_2O_5–K_2O$) used for growth sugarcane are 201.0 kg/ha (68.0 kg N/ha, 36.8 kg P_2O_5/ha, 96.2 kg K_2O/ha) without stillage application (scenario 1) and 71.8 kg/ha (50.0 kg N/ha, 8.4 kg P_2O_5/ha, 13.4 kg K_2O/ha) with stillage application (scenario 2). Diesel fuel used for cultivation and harvesting of sugarcane is 100.6 L/ha (scenario 1) and 134.7 L/ha (scenario 2). Lime, herbicides and insecticides have the same inputs values for both scenarios: 958.4 kg/ha, 2.2 kg/ha and 0.2 kg/ha, respectively. An average human labor of 0.70 man-hours/ha of sugarcane is required for both scenarios for all farming activities, including land preparation, planting, crop maintenance and harvesting. The transport distance assumed of the sugarcane from the field to the industrial facility of ethanol production is about 40 km by trucks of 45 t of capacity with an energy efficiency of 0.019 L/ton. km [93].

The assumed yield of ethanol was 86.5 $L_{ethanol}$/tc. The industrial processing of sugarcane to ethanol includes: NaOH (0.27 g/$L_{ethanol}$), H_2SO_4 (9.05 g/$L_{ethanol}$), C_6H_{12} (0.60 g/$L_{ethanol}$), lubricants (0.16 g/$L_{ethanol}$) and lime (10.50 g/$L_{ethanol}$). It was assumed that the sugarcane have an average sucrose content of 14.26% and 12.79% of bagasse, used as fuel to produce steam and electricity. Cogeneration plants, with steam cycle (2.2 MPa) were used in this study. The surplus electricity (12.0 kWh/tc) is sold to the public grid and can thus get the credits from avoided conventional electricity production [93].

The study of ethanol production from Macedo et al. [94] was based on the data from the 2002/2003 crop of the Center-South region of Brazil; the study with two scenarios: scenario 1 gives typical values of sugarcane and ethanol production, while scenario 2 was constructed with the best values so far observed, with the use of filter cake and stillage for fertilization of sugarcane fields and the improvement in industrial yield, with increased generation of bagasse and surplus electricity. The sugarcane productivity was 82.0 tc/ha and the industrial yield is about 88.7 L/tc (scenario 1) and 91.8 L/tc (scenario 2). Fertilizers used for sugarcane growth are 234.0 kg/ha (70.0 kg/ha N, 44.0 kg/ha P_2O_5 and 120.0 kg/ha K_2O) for scenario 1 and

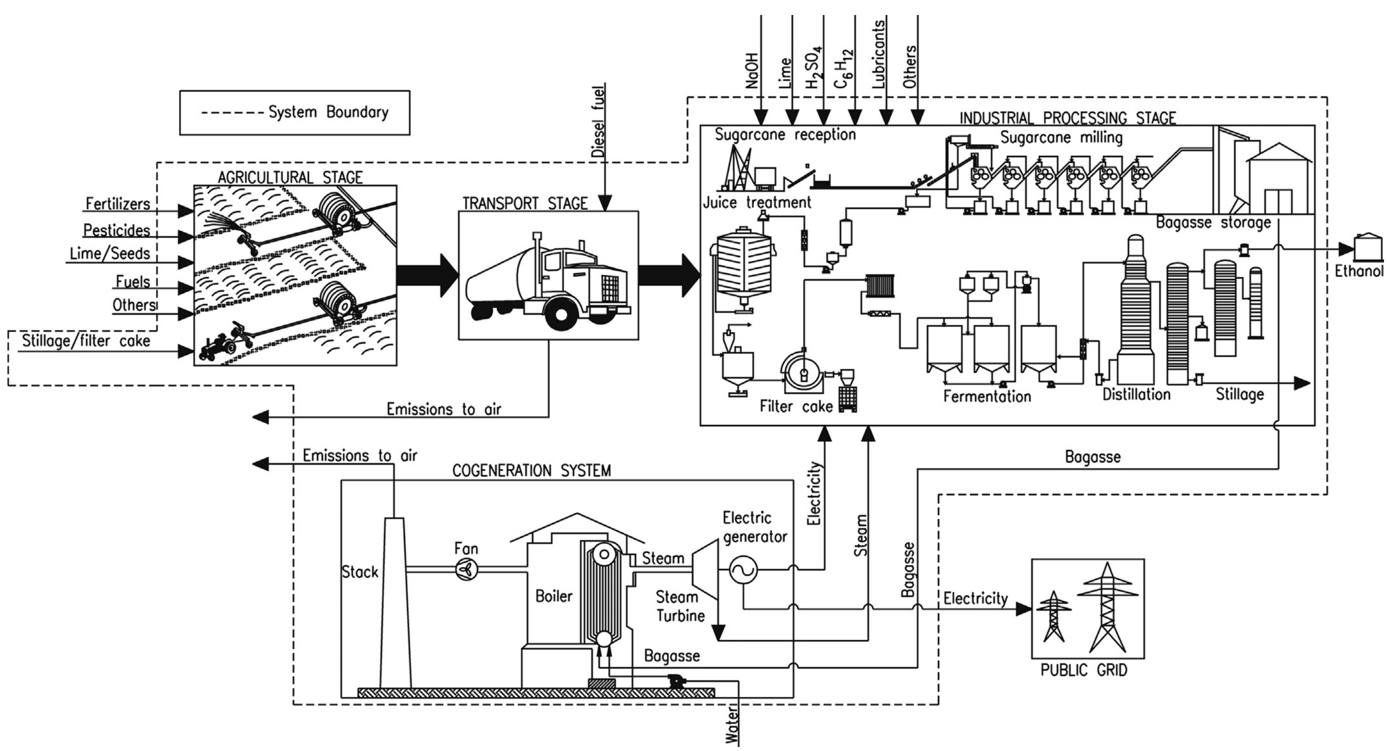


Fig. 1. Scheme of the system boundary of the ethanol production from sugarcane.

176.0 kg/ha (72.0 kg/ha N, 40.0 kg/ha P_2O_5 and 64.0 kg/ha K_2O) for scenario 2. Diesel fuel used for cultivation and harvesting of sugarcane is 114.2 L/ha (scenario 1) and 146.8 L/ha (scenario 2). Lime, herbicides and insecticides have the same inputs for both scenarios 2200 kg/ha, 2.4 kg/ha and 0.17 kg/ha, respectively. Sugarcane is transported to the sugar mill facility by trucks with diesel consumption of 67.3 L/ha (scenario 1) and 51.8 L/ha (scenario 2).

3.6. Biodiesel

3.6.1. Functional unit

The common base assumed was 1 MJ of energy released by combustion of biodiesel, based on its LHV (39.0 $MJ/kg_{biodiesel}$).

3.6.2. Life cycle boundaries

In soybean biodiesel production system boundary (Fig. 2), the agricultural stage boundary included soybean farming activities, such as, planting seeds, tillage, fertilizers ($N–P_2O_5–K_2O$), lime, herbicide, insecticide, diesel consumption for agricultural operations. Transportation takes the soybean from the field to the production facility. The industrial process of conversion of soybean to biodiesel consists of the vegetable oil extraction, feedstock pre-treatment and transesterification. The processing phase was divided in two stages: crushing/refining stage and transesterification are conducted inside the integrated facility, using hexane, methanol, water, electricity and fuels. This analysis excluded the assessments of energy consumption associated with facilities construction [121–124].

The LCA of palm oil biodiesel starts at the agricultural stage production of the palm oil and ends at this industrial conversion (Fig. 3). The system boundary in this study includes all major inputs and outputs for palm oil cultivation to produce FFB (agricultural stage), FFB crushing and refining to produce Refined Palm Oil (RPO), transportation of FFB from field to production facility (transportation stage) and transesterification stage. The analysis excluded the assessments of energy consumption associated with facilities construction [125–129].

3.6.3. Life cycle inventory

3.6.3.1. Soybean biodiesel. The primary base case data to carry out the LCA of soybean biodiesel in Brazil of this paper were collected from Capaz [93] and compared with the data collected from the literature. The data from industrial stage were obtained from equipment and plants manufacturers. In this study, considering the energy input from equipment and buildings and the energy balance resulted in 4.3 MJ_{output}/MJ_{input}.

Cavalett and Ortega [95] analyzed the biodiesel production from soybean under Brazilian conditions, using three indicators: material flow accounting, embodied energy analysis and emergy accounting. The boundary of the production system included agricultural step, transportation, crushing and industrial phase.

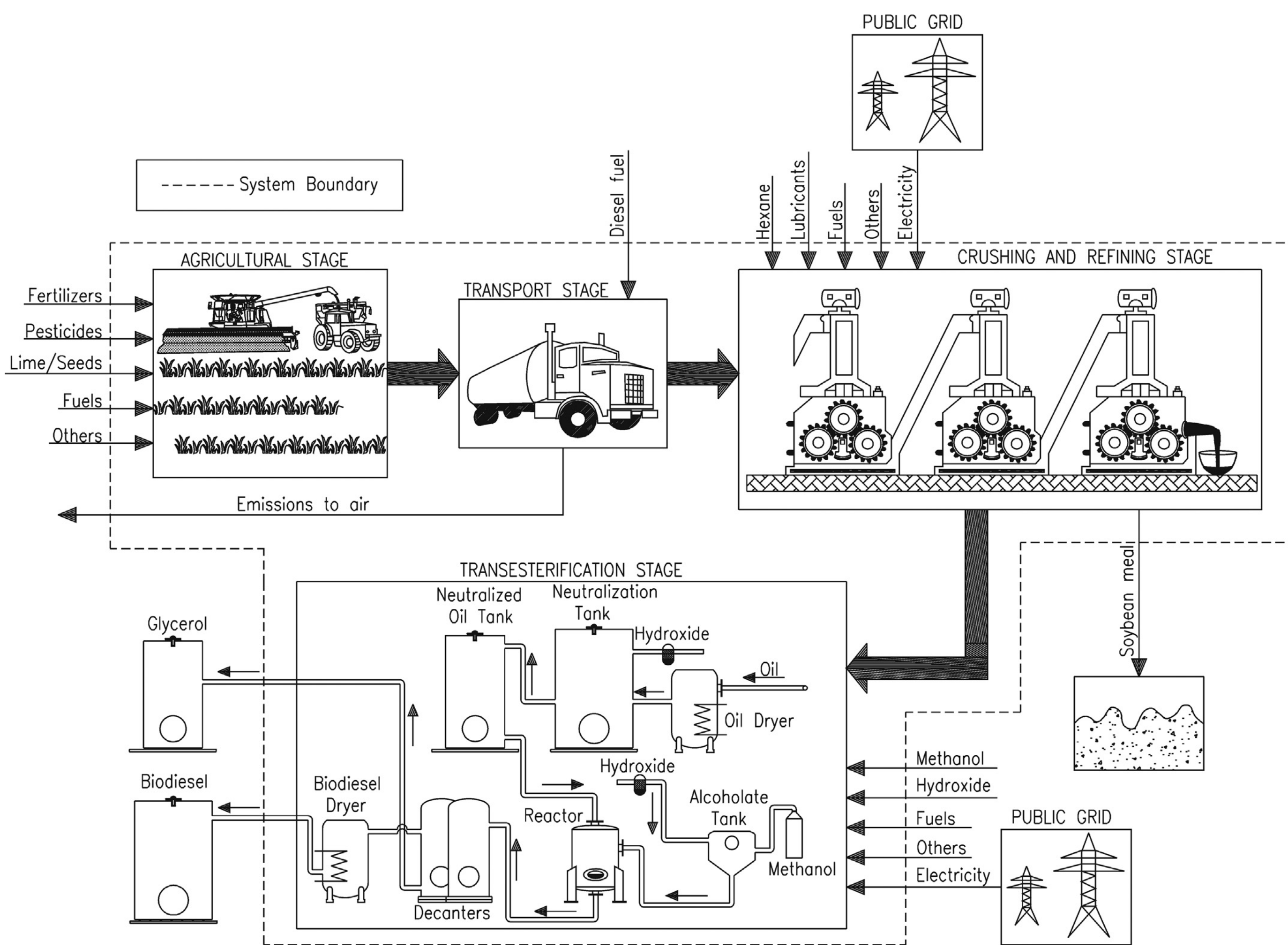


Fig. 2. Scheme of the system boundary of the biodiesel production from soybean.

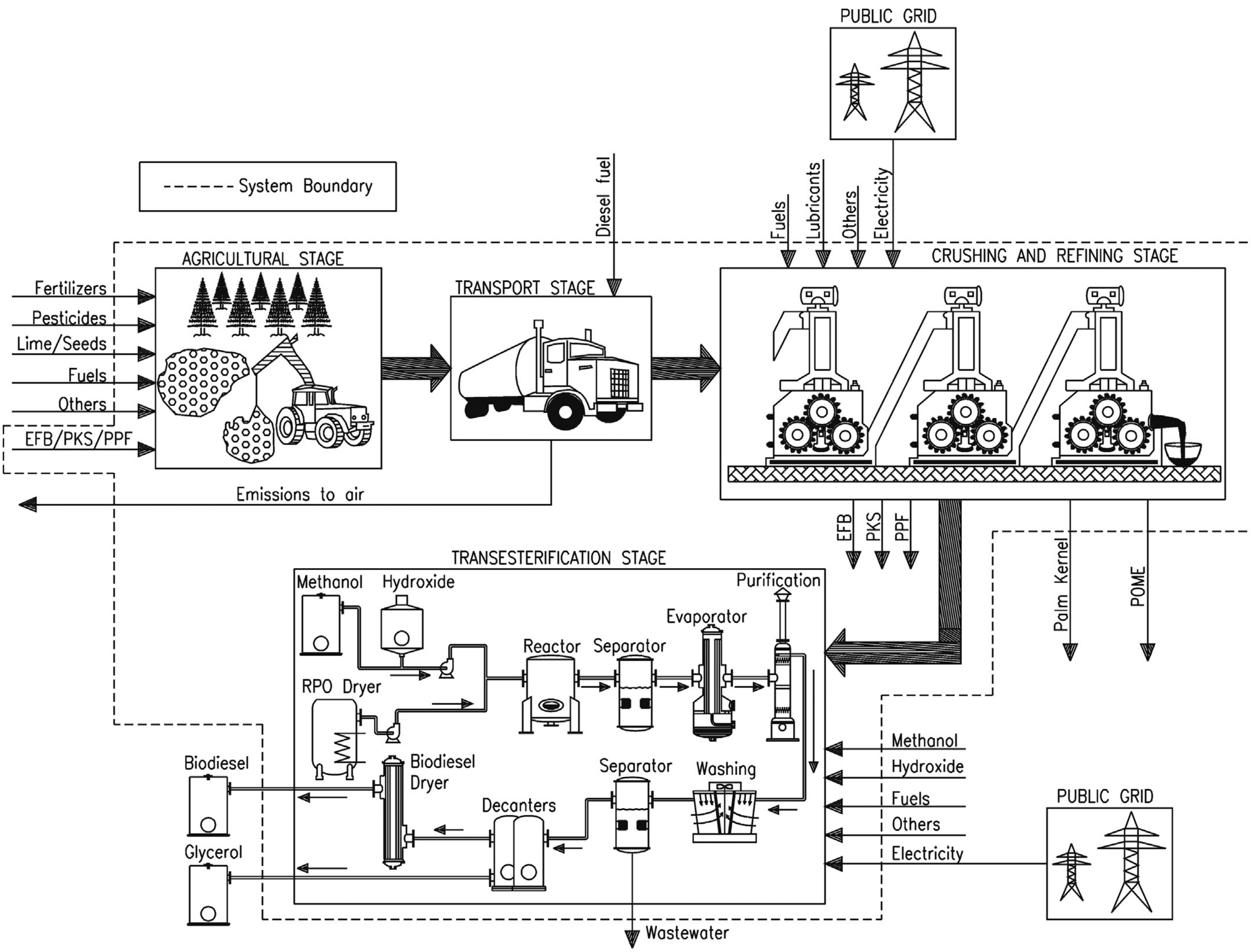


Fig. 3. Scheme of the system boundaries of the biodiesel production from palm oil.

The energy and CO_2 emissions analysis indicate greater values in agricultural and transesterification stages. The production of biodiesel from soybean returned 2.48 $MJ_{biodiesel}/MJ_{fossil\ energy}$ using energy allocation factors. They calculated the Energy Return on Investment (EROI), that is the amount of energy output divided by the energy invested by the economic system. The EROI calculated shows that 0.07 kg of crude oil equivalent is required to produce 1.0 kg of soybean, with an energy return of about 7.24 $J_{soybean}/J_{fossil\ fuel}$ invested.

Tsoutsos et al. [96] assessed the LCA of biodiesel from rapeseed, sunflower and soybean in Greek conditions. Alternative scenarios were constructed with variation of some parameters as fertilizing, water and fuel utilization. The major environmental impacts are caused by the consumption of fossil fuels and the use of fertilizers. By evaluating the crops for the biodiesel production, the production of biodiesel from rapeseed had the largest environmental impacts, while sunflower was more favorable and environmental friendly. The biodiesel from soybean presented the best values when they assessed the environmental impacts per harvested area, mainly in terms of the use of fertilizers, the methanol and energy requirements.

Pradhan et al. [97] carried out a LCA to quantify and compare the environmental performance and energy flows associated both, with biodiesel from soybean, in USA and petroleum-based diesel. The purpose of this analysis was to update the energy life cycle of the model to determine if any significant changes in the original inventory have occurred, since the model was first developed 10 years ago by Sheehan et al. [130]. The results showed an improvement in relation to previous study carried out by Sheehan et al. [130]. Pradhan et al. [97] showed the NER of the 4.45 based on data from 2002 of soybean production. This result was higher than the one of a previous study carried out by Sheehan et al. [130] that reported a NER of 3.2., indicating that the NER of biodiesel will continue to improve over time.

Carraretto et al. [98] investigated the performance of a boiler working with biodiesel from soybean and assessed the energy requirements and the total net emission of CO_2 during the whole life cycle of biodiesel produced in North-Italy, with a yield of 2445 kg/ha, the emissions of CO_2 from whole life cycle of biodiesel were 0.21 kg $CO_2/kg_{biodiesel}$ (null allocation). If the amount of CO_2 produced by processes is allocated on biodiesel, the emission is 0.72 kg $CO_2/kg_{biodiesel}$. The energy ratio was 2.04 $MJ_{biodiesel}/MJ_{fossil\ fuel}$. A summary of the inventory data for biodiesel production from soybean for the considered studies is shown in Table 5.

3.6.3.2. Palm oil biodiesel. The primary base case data to carried out the LCA of palm oil biodiesel of this paper were collected from Costa [99] and compared with data collected from the literature. The study by Costa [99] aimed to perform an inventory for the production of Palm Oil Methyl Ester (PME) in Colombia and Southeast of Bahia State and Amazon region in Brazil. In this study only data about the Amazon region will be used and referred

Table 5
Summary of inventory data for biodiesel production from soybean.

Parameter	Unit	Capaz [93]	Cavalett and Ortega [95]	Tsoutsos et al. [96]	Pradhan et al. [97]	Carraretto et al. [98]
Agricultural stage						
Productivity	kg/ha	3.15E+03	2.83E+03	2.71E+03	2.56E+03	2.45E+03
Nitrogen	$kg/MJ_{biodiesel}$	4.62E−05	–	2.39E−03	2.64E−04	2.20E−03
P_2O_5	$kg/MJ_{biodiesel}$	3.56E−03	1.45E−03	–	7.82E−04	1.18E−03
K_2O	$kg/MJ_{biodiesel}$	3.90E−03	2.79E−03	–	1.57E−03	1.41E−03
Lime	$kg/MJ_{biodiesel}$	2.40E−02	1.61E−02	–	2.21E−02	–
Diesel fuel	$kg/MJ_{biodiesel}$	1.47E−03	2.34E−03	–	1.80E−03	3.31E−03
Herbicide	$kg/MJ_{biodiesel}$	7.85E−05	2.05E−04	5.97E−05	7.46E−05	4.62E−05
Insecticide	$kg/MJ_{biodiesel}$	7.85E−05	1.37E−04	8.97E−05	1.24E−06	–
Lubricants	$kg/MJ_{biodiesel}$	–	–	–	–	9.00E−05
Seeds	$kg/MJ_{biodiesel}$	2.34E−03	2.95E−03	–	4.21E−03	6.41E−01
Gasoline	$kg/MJ_{biodiesel}$	–	–	–	5.00E−04	–
Natural gas	$kg/MJ_{biodiesel}$	–	–	–	1.46E−04	–
Propane	$kg/MJ_{biodiesel}$	–	–	–	8.28E−05	–
Transport stage						
Diesel fuel	$kg/MJ_{biodiesel}$	8.72E−03	1.82E−04	–	8.49E−04	7.18E−04
Crushing and Refining stage						
Soybean grains	$kg/MJ_{biodiesel}$	1.45E−01	1.21E−01	1.88E−01	1.41E−01	7.31E−02
Oil content	%	4.62E−01	4.62E−01	3.54E−01	4.87E−01	9.49E−01
Water	$kg/MJ_{biodiesel}$	–	8.74E−02	–	–	9.36E−03
Diesel fuel	$kg/MJ_{biodiesel}$	–	2.17E−03	–	–	–
Hexane	$kg/MJ_{biodiesel}$	2.56E−05	1.46E−04	–	2.85E−04	1.36E−04
Crude oil	$kg/MJ_{biodiesel}$	–	–	6.13E−03	–	–
Methane	$kg/MJ_{biodiesel}$	–	–	–	–	1.34E−03
Electricity	$kWh/MJ_{biodiesel}$	5.08E−03	–	8.87E−03	1.38E+00	5.44E−03
Transesterification stage						
Water	$kg/MJ_{biodiesel}$	–	1.11E−02	2.62E−02	–	–
Diesel fuel	$kg/MJ_{biodiesel}$	–	1.17E−03	–	–	–
NaOH	$kg/MJ_{biodiesel}$	2.05E−04	2.33E−04	2.09E−04	1.28E−04	5.90E−05
Methanol	$kg/MJ_{biodiesel}$	5.74E−03	3.23E−03	5.59E−03	3.82E−03	2.29E−03
Sodium methoxide	$kg/MJ_{biodiesel}$	–	–	–	3.21E−04	6.18E−04
Phosphoric acid	$kg/MJ_{biodiesel}$	–	–	1.55E−04	–	–
Hydrogen chloride	$kg/MJ_{biodiesel}$	–	–	–	1.82E−04	1.92E−04
Natural gas	$kg/MJ_{biodiesel}$	–	–	–	9.38E−04	–
Electricity	$kWh/MJ_{biodiesel}$	5.13E−04	–	1.79E−03	2.74E−03	–
Outputs						
Biodiesel	$kg/MJ_{biodiesel}$	2.56E−02	2.56E−02	2.56E−02	2.56E−02	2.56E−02
Glycerol	$kg/MJ_{biodiesel}$	2.90E−03	1.89E−03	–	3.56E−03	5.41E−03
Soybean meal	$kg/MJ_{biodiesel}$	1.19E−01	9.92E−02	1.62E−01	1.14E−01	4.59E−02

that the use of co-products, such as, PKS and PPF for steam and electricity generation for the process resulted in an impressive output/input energy indicator of 5.38, signalizing the potential use of this culture in biofuel production.

Kamahara et al. [100] evaluated the energy balance of PME in Indonesia. The results showed that the highest primary energy inputs in the palm tree biodiesel production life cycle were the methanol, the energy input in the biodiesel production processes and the nitrogen fertilizer production. These three items amounted for 85% of the total energy input. The results highlighted the importance of utilizing residues and co-products to improve energy efficiency. The calculated NER of PME in Indonesia was 3.10 $MJ_{biodiesel}/MJ_{input}$, considering only biodiesel as output, but this value could increase to 7.30 $MJ_{biodiesel}/MJ_{input}$, if the co-products are used to generate energy.

Papong et al. [101] analyzed the LCEA to produce PME in Thailand transport sector, based on a plant capacity of 500,000 L/day, the transesterification stage with an energy consumption (9.26 $MJ/kg_{biodiesel}$) due to methanol. The NER calculated, considering only the biodiesel output, was 2.48 MJ/MJ_{input}, and could increase up to 3.33 MJ/MJ_{input} if the co-products EFB, POME and PKS are considered as energy sources. If the steam and power production of the CPO mills are improved using a cogeneration system, the efficiency of the overall system is estimated at 60% and the energy output 11.87 MJ/kg_{PME}.

Souza et al. [102] assessed the production of PME in Amazon region in Brazil. The total energy input, without allocation of co-products was 790 MJ/kg_{PME}. If all co-products were used in the plant to supply steam and electricity, whose demand was of 8.98 MJ/kg_{PME}. The surplus of electricity was counted as output energy (2.76 $MJ/kg_{biodiesel}$), and together with PME resulted in 39.55 $MJ/kg_{biodiesel}$. The fuel consumption was responsible for 18% of the GHG emissions in the palm biodiesel life cycle. The NER calculated in their study resulted in 5.37 MJ/MJ_{input}, with 1437 kg CO_{2eq}/ha, which can reduce 80.0 g CO_{2eq}/MJ in comparison of diesel.

The LCEA of PME analyzed by Pleanjai and Gheewala [103] in Thailand in perspective. The transportation distance is responsible by 30% of the energy consumption. Together with methanol and fertilizers, they were responsible by more than 85% of energy consumption. An important point considered was the use of co-products for electricity and steam generation. In this way, the NER of PME without co-products was 2.42 MJ/MJ_{input}, which is still higher than 1.0, indicating a favorable result. A summary of the inventory data for PME of all the studies is shown in Table 6.

4. Results and discussion

As shown above, the biofuel production systems were analyzed using five environmental impacts, that are functions of mass/energy input inventories and emissions (soil, water and air) output inventories.

Table 6
Summary of inventory data for PME production.

Parameter	Unit	Costa [99]	Kamahara et al. [100]	Papong et al. [101]	Souza et al. [102]	Pleanjai and Gheewala [103]
Agricultural stage						
Productivity FFB	kg FFB/ha	2.50E+04	1.76E+04	1.65E+04	2.04E+04	1.72E+04
Nitrogen	kg/$MJ_{biodiesel}$	7.28E−04	1.81E−03	1.03E−03	2.67E−04	1.38E−03
P_2O_5	kg/$MJ_{biodiesel}$	7.28E−04	1.49E−03	1.28E−03	5.21E−04	8.97E−06
K_2O	kg/$MJ_{biodiesel}$	2.67E−03	1.80E−03	3.08E−03	9.56E−04	2.56E−03
Magnesium	kg/$MJ_{biodiesel}$	1.46E−04	1.62E−03	–	7.46E−05	1.25E−03
Boron	kg/$MJ_{biodiesel}$	4.85E−05	1.91E−03	1.17E−04	3.69E−05	1.11E−04
Diesel fuel	kg/$MJ_{biodiesel}$	2.59E−04	1.22E−04	9.90E−05	–	4.31E−05
Herbicide	kg/$MJ_{biodiesel}$	1.60E−08	1.67E−06	1.46E−05	1.62E−05	4.97E−05
Insecticide	kg/$MJ_{biodiesel}$	9.28E−06	1.24E−08	6.67E−06	7.77E−06	1.77E−05
Lubricants	kg/$MJ_{biodiesel}$	1.33E−05	–	–	–	–
Seeds	kg/$MJ_{biodiesel}$	2.16E−04	–	–	1.16E−03	1.74E−03
Gasoline	kg/$MJ_{biodiesel}$	5.18E−07	–	1.33E−05	–	–
Transport stage						
Diesel fuel	kg/$MJ_{biodiesel}$	3.79E−04	1.15E−04	1.08E−03	7.82E−04	1.77E−03
Crushing and Refining stage						
FFB input	kg/$MJ_{biodiesel}$	1.35E−01	1.25E−01	1.07E−01	1.32E−01	1.79E−01
Oil content	%	4.92E−01	5.51E−01	8.31E−01	5.26E−01	4.18E−01
Water	kg/$MJ_{biodiesel}$	4.54E−02	–	6.49E−02	4.69E−02	5.67E−02
Diesel fuel	kg/$MJ_{biodiesel}$	2.36E−04	1.51E−04	7.59E−05	7.18E−05	1.39E−04
Electricity	kWh/$MJ_{biodiesel}$	2.69E−03	5.13E−04	2.05E−03	2.69E−03	2.48E−04
Outputs						
CPO	kg/$MJ_{biodiesel}$	2.59E−02	2.69E−02	3.46E−02	2.69E−02	2.92E−02
Palm kernel	kg/$MJ_{biodiesel}$	3.82E−03	5.38E−03	7.56E−04	7.00E−03	9.59E−03
Fibers	kg/$MJ_{biodiesel}$	1.72E−02	1.76E−02	2.77E−02	1.71E−02	5.08E−02
Palm shells	kg/$MJ_{biodiesel}$	1.17E−02	6.69E−03	5.90E−03	9.23E−03	1.17E−02
POME	kg/$MJ_{biodiesel}$	9.46E−02	4.44E−02	7.51E−02	8.85E−02	8.62E−02
EFB	kg/$MJ_{biodiesel}$	2.69E−02	3.13E−02	2.77E−02	2.97E−02	4.82E−02
Transesterification stage						
Water	kg/$MJ_{biodiesel}$	3.72E−03	–	–	–	5.13E−03
NaOH	kg/$MJ_{biodiesel}$	5.13E−05	2.35E−04	1.50E−04	1.55E−04	2.56E−04
Diesel fuel	kg/$MJ_{biodiesel}$	–	–	–	4.82E−04	3.15E−05
Methanol	kg/$MJ_{biodiesel}$	2.54E−03	3.46E−03	4.62E−03	2.56E−03	4.62E−03
Sodium methoxide	kg/$MJ_{biodiesel}$	1.28E−04	–	–	–	–
Sulfuric acid	kg/$MJ_{biodiesel}$	–	–	–	1.38E−04	–
Hydrogen chloride	kg/$MJ_{biodiesel}$	2.56E−04	–	–	–	–
Fuel oil	kg/$MJ_{biodiesel}$	–	–	7.69E−04	–	–
Electricity	kWh/$MJ_{biodiesel}$	2.95E−04	7.87E−03	1.28E−05	4.26E−03	2.12E−03
Outputs						
Biodiesel	kg/$MJ_{biodiesel}$	2.56E−02	2.56E−02	2.56E−02	2.56E−02	2.56E−02
Glycerol	kg/$MJ_{biodiesel}$	2.97E−03	4.28E−03	5.38E−03	8.10E−03	4.62E−03

4.1. *Ethanol*

4.1.1. *Life cycle impact assessment*

4.1.1.1. Abiotic depletion potential. The ADP impact category measures the consumption of non-renewable resources during the WTT life cycle of biofuel produced via different processes. Fig. 4 illustrates the ADP environmental impact of ethanol production. The ADP of the analyzed studies ranges from 1.05E−4 kg Sb-eq./$MJ_{ethanol}$ (Capaz [93]) to 1.27E−4 kg Sb-eq./$MJ_{ethanol}$ (Macedo et al. [94]).

As pointed out in both studies, agricultural stage has the highest impacts on ADP, due to the large consumption of fertilizers, diesel fuel and lime. A comparison of two studies showed that the one done by Capaz [93] presented the best values of ADP environmental impact in relation to the Macedo et al. [94], because inventory data correspond to an increase of low tillage practices and mechanical planting. Two more works were included to compare the environmental impacts with the selected studies for sugarcane ethanol meta-analysis.

Luo et al. [131] carry out a comparative LCA study to analyze the Brazilian ethanol production from sugarcane with two cases: base case (electricity generation from bagasse) and future case (ethanol production from both sugarcane and bagasse and electricity generation from wastes). In both cases sugar was a co-product. The LCIA method considered in the evaluation of the impacts was the CML 2000. The FU assumed was 1.0 km of driving midsize car. When the data is set at the same level of FU, the reported value by Luo et al. [131] for ACP is 8.70E−5 kg Sb-eq./$MJ_{ethanol}$.

Cavalett et al. [132] carried out a study that makes a comparison between environmental impacts of gasoline and ethanol production from sugarcane in Brazil. The LCIA methods considered in the evaluation of the impacts were: CML 2001, Impact 2002+, EDIP 2003, Eco-Indicator 99, TRACI 2, ReCiPe and Ecological Scarcity 2006. The boundaries included: harvesting, transport, industrial ethanol production, distribution and final use of fuel; the FU assumed by Cavalett et al. [132] was 1.0 MJ of fuel (gasoline or ethanol). The results reported by the authors for ADP were 7.67E−5 kg Sb-eq./$MJ_{ethanol}$.

4.1.1.2. Global warming potential. The GWP environmental impact in the analyzed studies are shown in Fig. 5. The GWP of the analyzed studies ranges from 3.60E−3 kg CO_2-eq./$MJ_{ethanol}$ (Macedo et al. [94]) to 6.26E−3 kg CO_2-eq./$MJ_{ethanol}$ (Capaz [93]).

In ethanol studies, the increasing mechanization of the agriculture, the pre-burning in the harvesting and the transport, are responsible for the most of the emissions. The ethanol production presented low values (on average of 4.93 g CO_2-eq./$MJ_{ethanol}$) because the high agricultural yield (an average of 83 tc/ha), the use of bagasse to generate power and steam for the process and

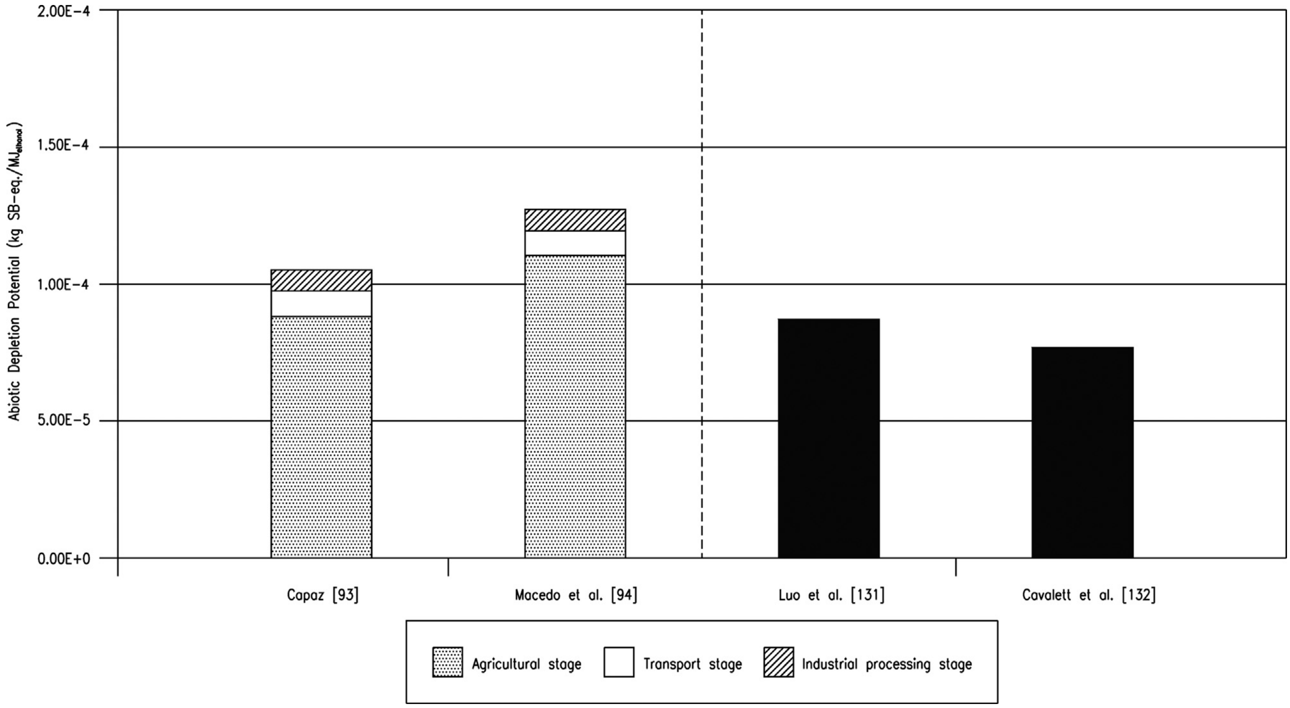


Fig. 4. ADP in life cycle of ethanol production.

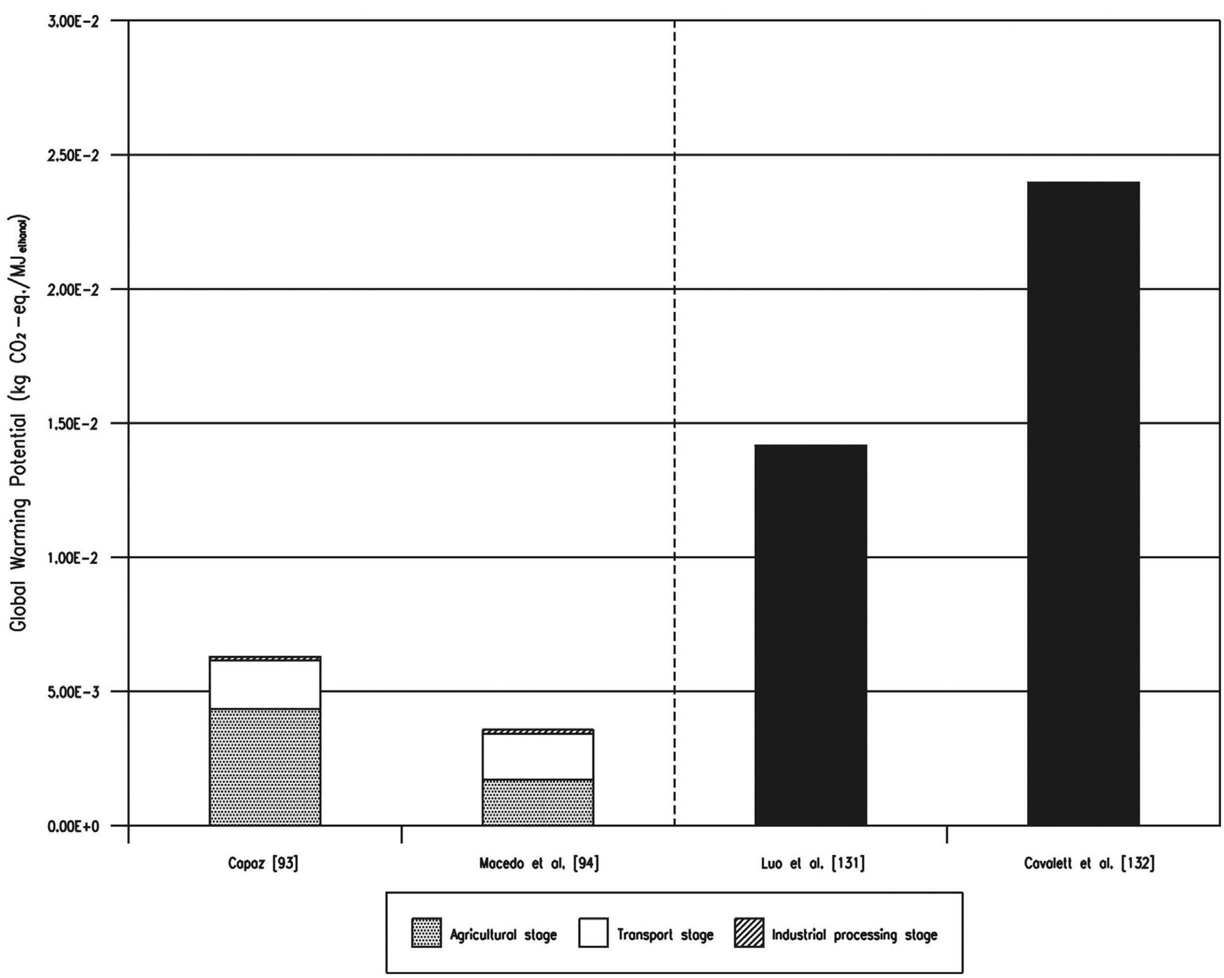


Fig. 5. GWP in life cycle of ethanol production.

also the use of the stillage and filter cake as fertilizers in the agricultural stage. The high productivity results in lower energy input in the agricultural stage, which is mainly referred to the consumption of diesel in agricultural operations. The intensification of mechanization results in an increase of the GHG emissions. Capaz [93] accounted 50% of the mechanical harvesting, in contrast to Macedo et al. [94] that registered about 36%.

The calculated values of gaseous emissions of CO_2-eq./$MJ_{ethanol}$ from ethanol process are different from Luo et al. [131], because their study considers the transport and utilization of ethanol as vehicular fuel. The result presented by Cavalett et al. [132] to GWP for ethanol chain is 2.40E−2 kg CO_2-eq./$MJ_{ethanol}$, because consider the Well-to-Wheel (WTW) analysis.

Seabra and Macedo [120] reported that the comparison between GHG emissions for ethanol and electricity production are difficult, because of the life cycle boundaries of the study and the inclusion of co-products credits and allocation of this co-products. The authors reported ethanol life cycle GHG emissions between 5.0 and 19.0 g CO_2-eq./$MJ_{ethanol}$ produced.

The results of the LCA studies strongly depend on the quality of the information given as input. Understanding this issue, becomes of primary importance, when the LCA approach is applied to provide quantitative assessments, for very large and complex chains, as it is the case of biofuels. Therefore, the results of LCA studies could be different for various reasons, among them the region, the agricultural and industrial practices, the inventory data, etc.

4.1.1.3. Human toxicity potential. The HTP environmental impact is mainly attributed to herbicides, pesticides and fertilizer utilization in agricultural activities for biofuels production. Pesticides are biologically active substances with a compound-specific inherent toxicity and contain heavy metals, such as Cd, Zn, Co, Se and Hg, with high impact over the aquatic and terrestrial ecotoxicity and human toxicity [133].

The HTP values of the analyzed studies are shown in Fig. 6. The HTP of the analyzed studies ranges from 1.74E−4 kg 1,4 DB-eq./$MJ_{ethanol}$ (Macedo et al. [94]) to 2.38E−4 kg 1,4 DB-eq./$MJ_{ethanol}$ (Capaz [93]). When the energy used in the industrial process of ethanol production is generated by self-production through co-products (bagasse), the HTP impact, via air, is lower because the CML 2 Baseline 2000 method considers the emissions of NH_3, NO_2, NO_x and NH_4^+ to air.

The HTP impact through air and water are the most significant potential impacts for the life cycle of ethanol. The contribution to HTP environmental impact in the agricultural stage were

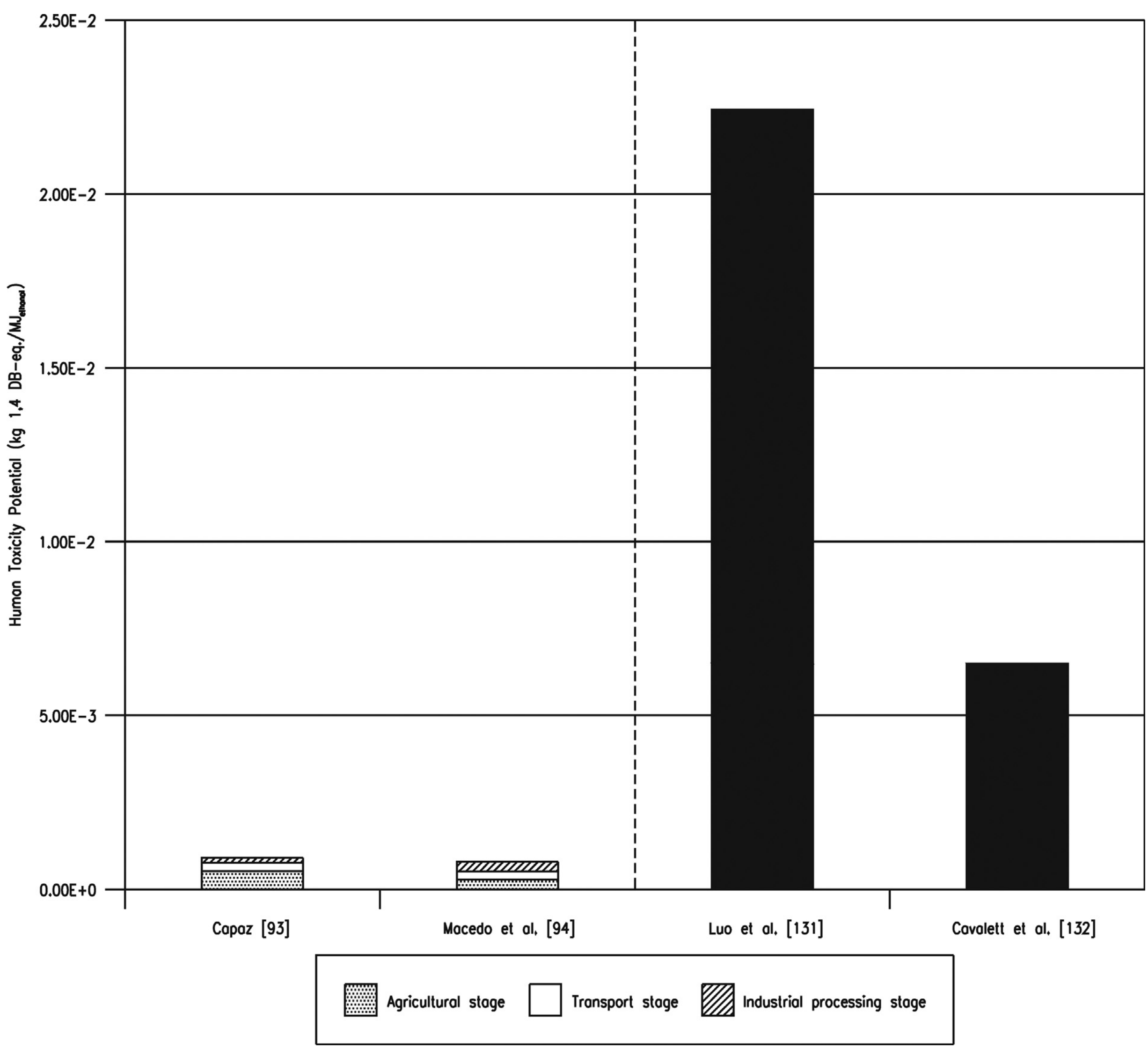


Fig. 6. HTP in life cycle of ethanol production.

accounted by Capaz [93] (57%) and Macedo et al. [94] (36%), the transport stage for Capaz [93] (27%) and for Macedo et al. [94] (29%); the industrial processing stage after Capaz [93] (15%) and for Macedo et al. [94] (35%). In the same FU basis, the HTP environmental impact by Luo et al. [131] is 2.24E−2 kg 1,4 DB-eq./$MJ_{ethanol}$ and by Cavalett et al. [132] the HTP is 6,59E−3 kg 1,4 DB-eq./$MJ_{ethanol}$.

4.1.1.4. Acidification potential. This impact category derives from acidifying pollutants, such as NH_3, NO_2, NO_x, SO_2 and SO_x reaching the atmosphere and reacting with water vapor to form acids. In this study, ACP results, mainly from the emissions of SO_2 and NO_x, are shown in Fig. 7. The agricultural stage presented the largest contribution, due to the use of fertilizers and chemicals (herbicides and pesticides).

The ACP of the analyzed studies ranges from 7.86E−5 kg SO_2-eq./$MJ_{ethanol}$ (Macedo et al. [94]) to 9.81E−5 kg SO_2-eq./$MJ_{ethanol}$ (Capaz [93]). Acidifying emissions are generally related to combustion of fossil fuels, hence the transportation stage is responsible for 24% of the ACP impacts (Capaz [93]) and 29% (Macedo et al. [94]). The agricultural stage accounts for 59% of the impacts in this category (Capaz [93]) and 50% (Macedo et al. [94]), due mainly to fertilizers production and utilization and emissions of SO_2 from phosphate fertilizer. Luo et al. [131] reported value of ACP impact of 4.90E−4 kg SO_2-eq./$MJ_{ethanol}$ and the result presented by Cavalett et al. [132] for ACP impact is 3.98E−4 kg SO_2-eq./$MJ_{ethanol}$.

4.1.1.5. Eutrophication potential. The ETP covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are N–P_2O_5. Nutrient enrichment may cause an increase in the aquatic plant growth and/or the shift in species composition in both aquatic and terrestrial ecosystems. consumption of oxygen the biomass decomposition.

In this study, it was considered that the emissions of NH_3, HNO_3, NO, NO_2,NO_3^-, NH_4^+ to air and Chemical Oxygen Demand (COD), Total-P, Total-N, phosphorus (P), H_3PO_4, NO_3^-, NO_2^-, NO, NO_x emissions to water contribute to the ETP. Fig. 8 shows that the agricultural stage is responsible for the major individual indexes of contribution to this environmental impact category.

The ETP of the analyzed studies ranges from 1.66E−5 kg PO_4^{-3}-eq./$MJ_{ethanol}$ (Macedo et al. [94]) to 2.13E−5 kg PO_4^{-3}-eq./$MJ_{ethanol}$ (Capaz [93]). The contribution to ETP environmental impact of the agricultural stage by Capaz [93] is 72% and by Macedo et al. [94] 65%. The transport stage can contributes with 28% (Capaz [93]) and 35% (Macedo et al. [94]). The industrial processing stage could be negligible in relation to this impact category. Luo et al. [131] reported value of ETP of 1.27E−4 kg PO_4^{-3}-eq./$MJ_{ethanol}$ and the result presented by Cavalett et al. [132] for ETP is 9.73E−5 kg PO_4^{-3}-eq./$MJ_{ethanol}$.

4.2. Biodiesel

4.2.1. Life cycle impact assessment

4.2.1.1. Abiotic depletion potential. Fig. 9 shows the ADP environmental impact of biodiesel production. The ADP of biodiesel from soybean in the analyzed studies ranges from 1.06E−4 kg Sb-eq./$MJ_{biodiesel}$ (Capaz [93]) to 7.46E−4 kg Sb-eq./$MJ_{biodiesel}$ (Tsoutsos et al. [96]). The ADP of biodiesel from palm oil at the analyzed studies ranges from 8.50E−5 kg Sb-eq./$MJ_{biodiesel}$ (Souza et al. [102]) to 4.48E−4 kg Sb-eq./$MJ_{biodiesel}$ (Kamahara et al. [100]). The base case study of Costa [99] present a ADP of 2.45E−4 kg Sb-eq./$MJ_{biodiesel}$.

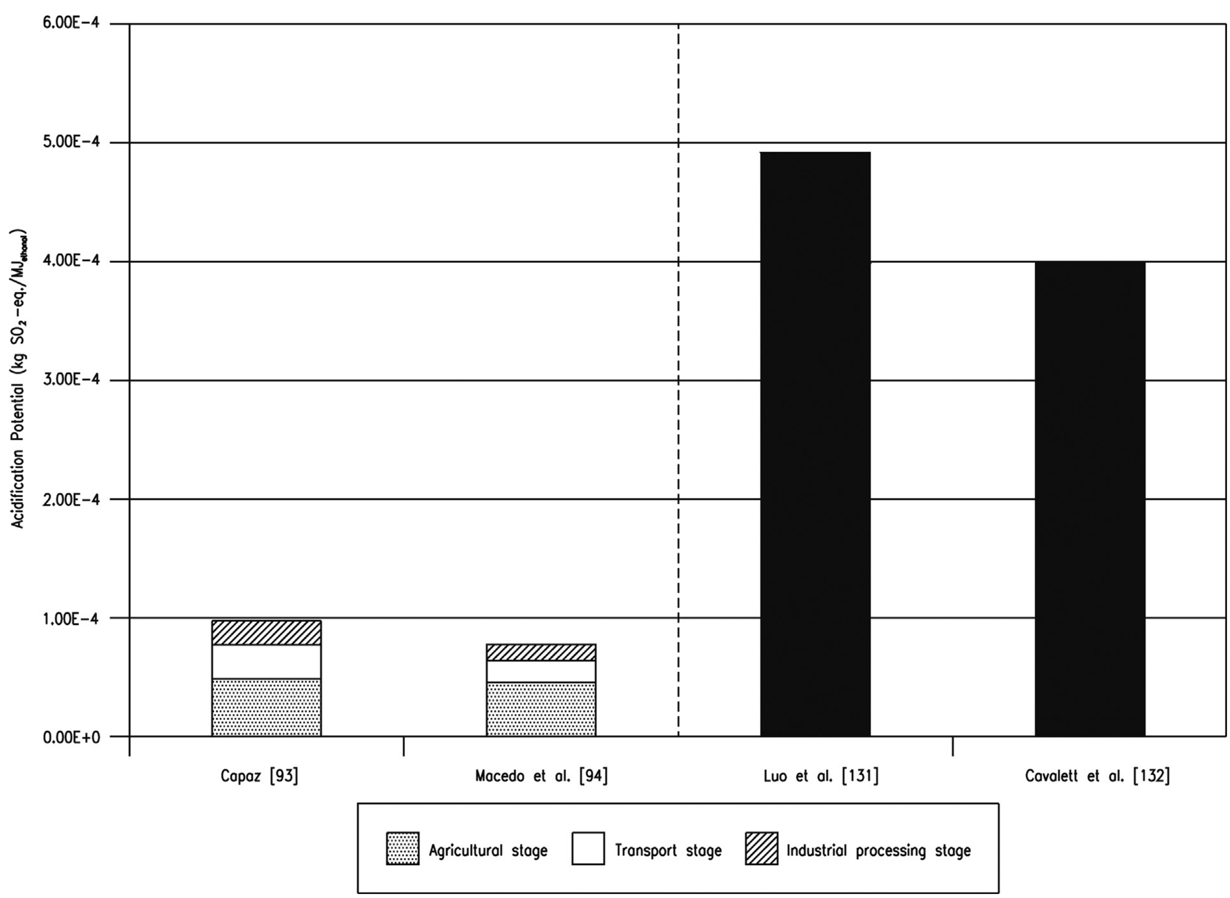


Fig. 7. ACP in life cycle of ethanol production.

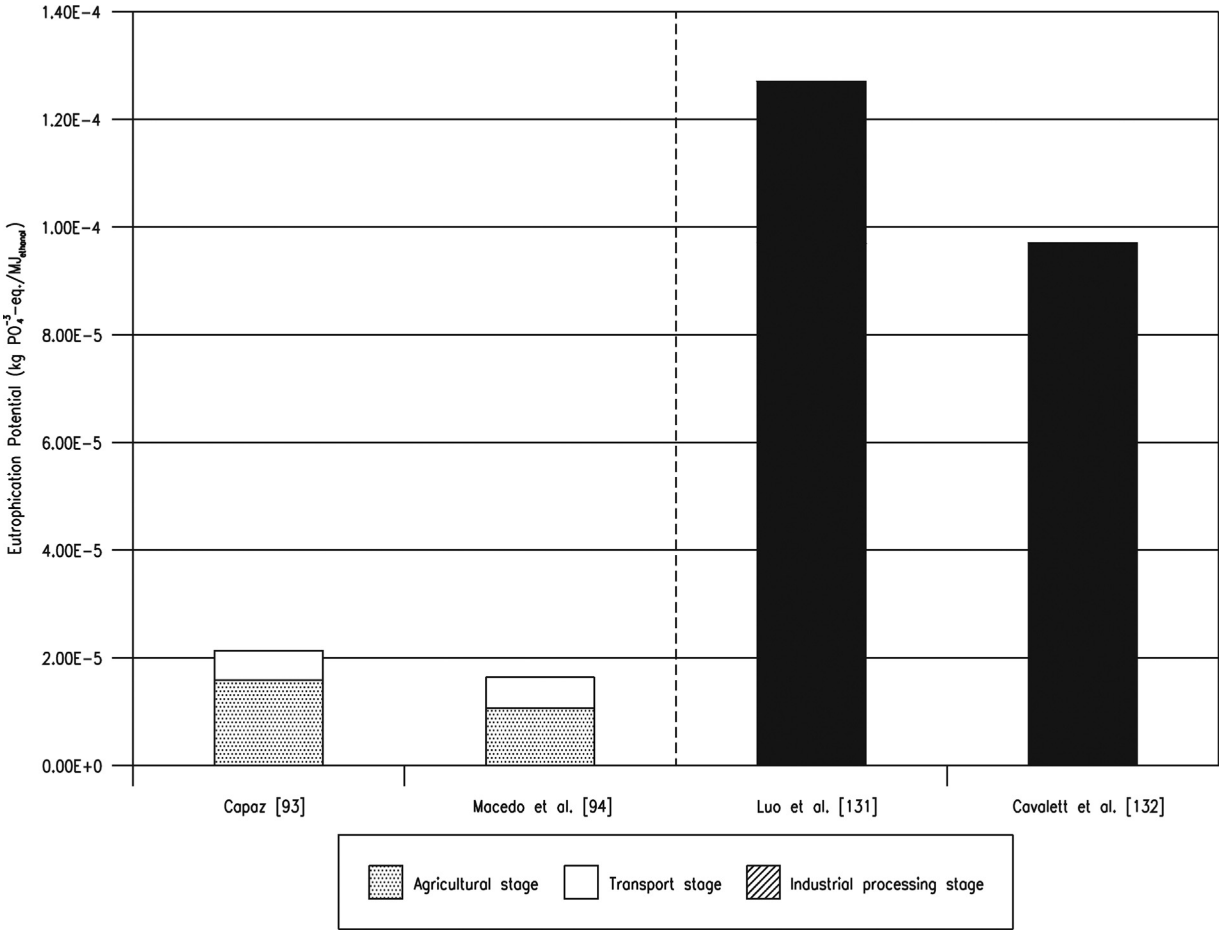


Fig. 8. ETP in life cycle of ethanol production.

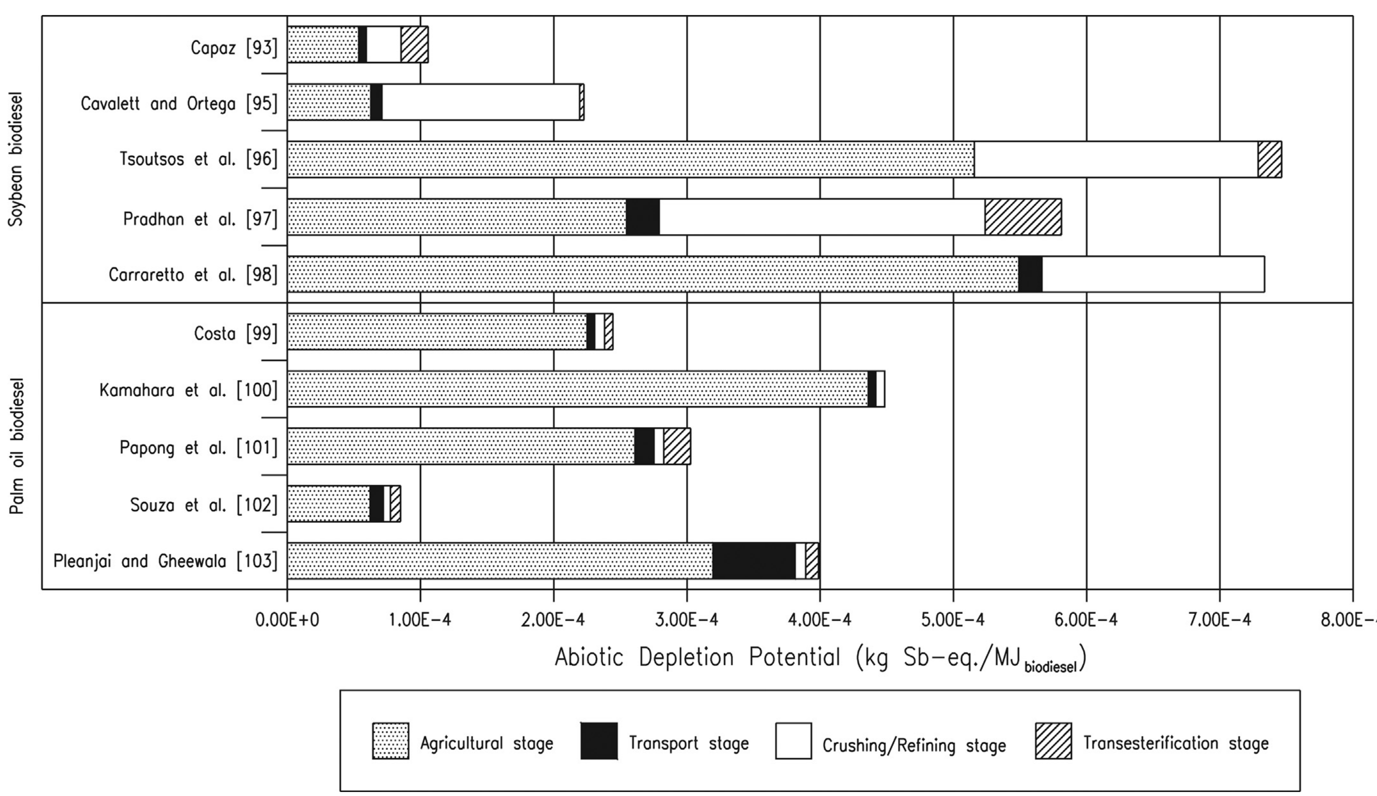


Fig. 9. ADP in life cycle of biodiesel production.

In general the agricultural stage presents the highest values because of the consumption of chemicals and fertilizers. In the case of soybean biodiesel, the crushing and refining stage shows higher values in comparison with the palm oil biodiesel, due to the intense use of electricity and crude oil (Tsoutsos et al. [96]), diesel and electricity (Cavalett and Ortega [95]) and natural gas (Pradhan et al. [97]). In the palm oil biodiesel is common the use of co-products to generate power and steam for the process, that justified the lowest values, except in Kamahara et al. [100] and Papong et al. [101] that presents high values to this impact, due to the consumption of magnesium and boron in this stage. Two more works were included to compare the environmental impacts with the selected studies for meta-analysis.

Hou et al. [134] assumed that the FU was 1.0 MJ of energy from biodiesel in the WTW perspective. The boundaries included production of chemicals and process energy, agriculture of biomass feedstock, production of biodiesel, biomass and biodiesel transport sections and final vehicle use operations. The reported result by the authors to ADP of biodiesel production from soybean was 1.68E−4 kg Sb-eq./$MJ_{biodiesel}$.

Silalertruksa and Gheewala [135] carried out a study to assess the environmental sustainability of palm oil biodiesel in Thailand, but it will not be possible to compare the obtained results of ADP because the authors did not assess the ADP environmental impact category.

4.2.1.2. Global warming potential. Fig. 10 shows the GWP environmental impact of biodiesel production. The GWP impact of the biodiesel from soybean, in the analyzed studies, ranges from 8.04E−3 kg CO_2-eq./$MJ_{biodiesel}$ (Capaz [93]) to 4.25E−2 kg CO_2-eq./$MJ_{biodiesel}$ (Pradhan et al. [97]). The GWP impact of biodiesel from palm oil in the analyzed studies ranges from 1.74E−3 kg CO_2-eq./$MJ_{biodiesel}$ (Kamahara et al. [100]) to 1.29E−2 kg CO_2-eq./$MJ_{biodiesel}$ (Pleanjai and Gheewala [103]). The base case study Costa [99] present a GWP of 3.12E−3 kg CO_2-eq./$MJ_{biodiesel}$.

The palm oil biodiesel system presented low GWP values (on average 5.1 g CO_2-eq./$MJ_{biodiesel}$) because of the high agricultural yield (19.0 t FFB/ha) and the use of agricultural residues to generate power and steam for the process. The transport stage (Papong et al. [101]; Souza et al. [102]; Pleanjai and Gheewala [103]) and industrial stage (Cavalett and Ortega [95]; Tsoutsos et al. [96]; Pradhan et al. [97]; Carraretto et al. [98] and Costa [99]) are generally responsible for the major emissions of GHG during the life cycle of biodiesel production.

In Pleanjai and Gheewala [103] the transport stage was responsible for 86% of total emissions (12.9 g CO_2 eq./$MJ_{biodiesel}$) due to the inefficient logistic between field and mill, using truck transport in almost 1500 km of distance. On average, biodiesel Brazilian base case studies (Capaz [93] and Costa [99]) presented low values, one of the causes is the low distance to transport (near to 20 km).

The reported result by Huo et al. [134] to GWP for biodiesel production from soybean was 3.51E−2 kg CO_2-eq./$MJ_{biodiesel}$. When the data is set on the same level of FU the reported result by the Silalertruksa and Gheewala [135] to GWP for biodiesel production from palm oil was 3.44E−2 kg CO_2-eq./$MJ_{biodiesel}$.

4.2.1.3. Human toxicity potential. The focus of HTP impact category is the long-term exposure to chemicals in the regional and global environment estimated through the acceptable daily intake and predicted daily intake. In the results, HTP is originated from emissions of NO_x, SO_2 and particulates. As the substances causing HTP are mostly the same as the acidifying substances, the stages contributing mainly to the two impact categories (terrestrial and aquatic ecotoxicity) are also similar. Fig. 11 illustrates the impacts related the HTP for biodiesel production.

The HTP impact of biodiesel from soybean from the analyzed studies ranges from 1.52E−3 kg 1,4 DB-eq./$MJ_{biodiesel}$ (Capaz [93]) to 8.70E−3 kg 1,4 DB-eq./$MJ_{biodiesel}$ (Pradhan et al. [97]). The HTP impact of biodiesel from palm oil of the analyzed studies ranges

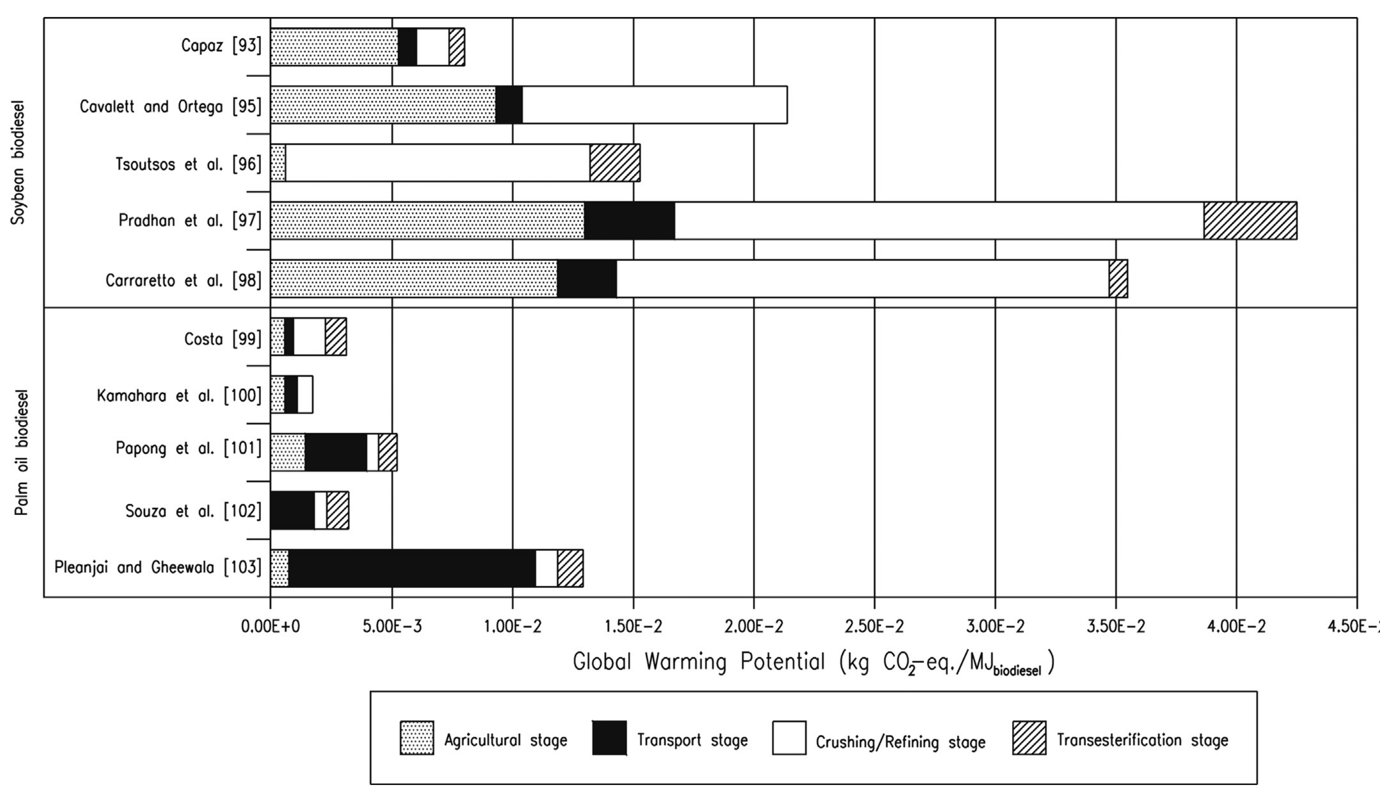


Fig. 10. GWP in life cycle of biodiesel production.

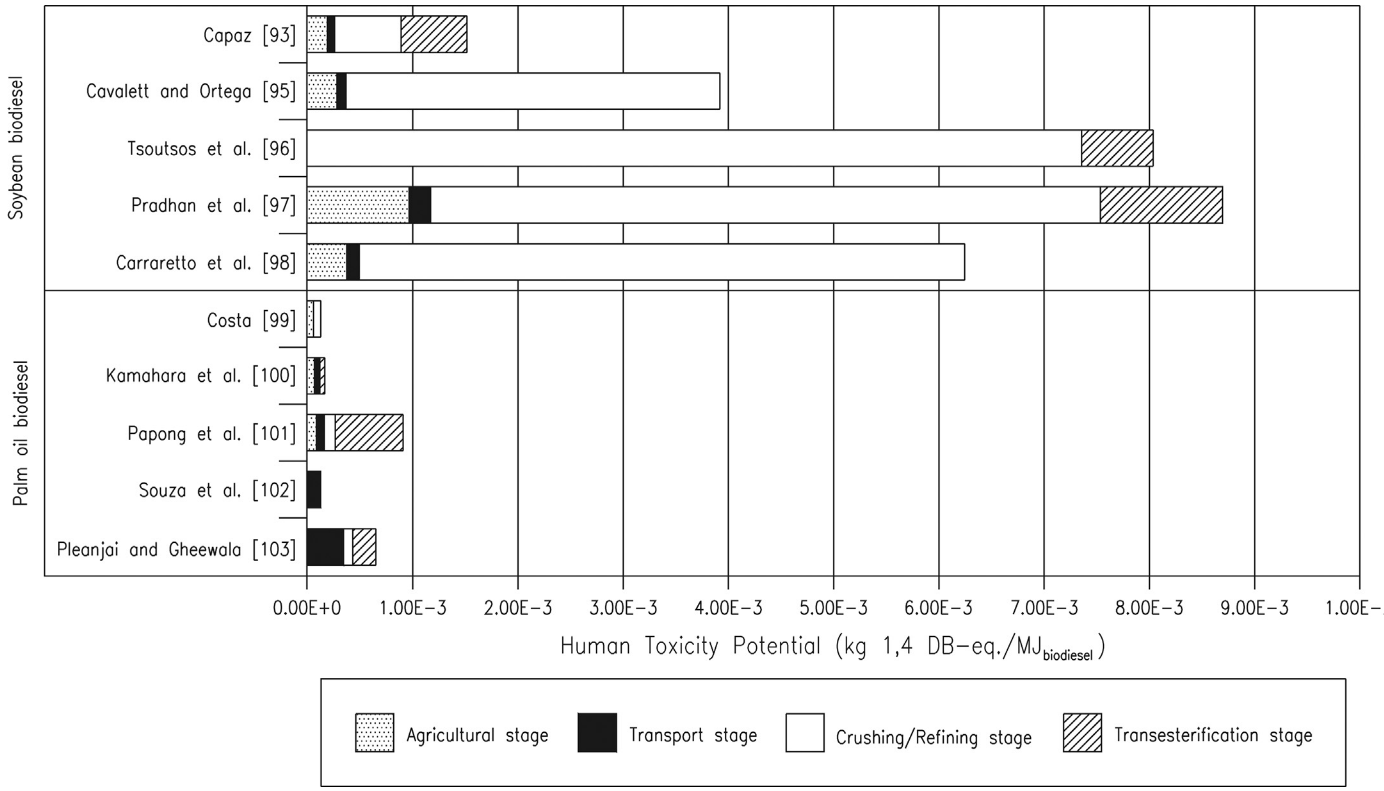


Fig. 11. HTP in life cycle of biodiesel production.

from 1.31E−4 kg 1,4 DB-eq./$MJ_{biodiesel}$ (Souza et al. [102]) to 9.15E−4 kg 1,4 DB-eq./$MJ_{biodiesel}$ (Papong et al. [101]). The base case study of Costa [99] present a HTP of 1.37E−4 kg 1,4 DB-eq./$MJ_{biodiesel}$.

In terms of HTP, the impact was huge, mainly in soybean biodiesel production, during oil extraction due to the fossil fuels consumption, for instance fuel oil (Capaz [93]; Cavalett and Ortega [95] and Tsoutsos et al. [96]), natural gas (Pradhan et al. [97]) and electricity (Carraretto et al. [98]). The same is observed in ACP, when the use of fertilizers and pesticides determines high impacts.

The conversion stage presented high values to HTP because in the transesterification step fuel oil (Capaz [93] and Papong et al. [101]), natural gas (Pradhan et al. [97]) and electricity (Tsoutsos et al. [96] and Pleanjai and Gheewala [103]). When the energy used in the industrial process of palm oil biodiesel production is generated through co-products (PKS, EFB and POME) the HTP impacts are lower (Costa [99]; Kamahara et al. [100] and Souza et al. [102]). The result presented by Huo et al. [134] to HTP for biodiesel from soybean was 1.29E−2 kg 1,4 DB-eq./$MJ_{biodiesel}$. The ones presented by Silalertruksa and Gheewala [135] to HTP for biodiesel production from palm oil was 6.85E−5 kg 1,4 DB-eq./$MJ_{biodiesel}$.

4.2.1.4. Acidification potential. The ACP impact from the emissions of SO_2 and NO_x, are according to Fig. 12. The ACP of biodiesel from soybean in the analyzed studies ranges from 1.37E−4 kg SO_2-eq./$MJ_{biodiesel}$ (Tsoutsos et al. [96]) to 3.80E−4 kg SO_2-eq./$MJ_{biodiesel}$ (Pradhan et al. [97]). The base case study Capaz [93] presents an ACP of 1.65E−4 kg SO_2-eq./$MJ_{biodiesel}$. The ACP of biodiesel from palm oil, in the analyzed studies, ranges from 5.21E−5 kg SO_2-eq./$MJ_{biodiesel}$ (Costa [99]) to 2.01E−4 kg SO_2-eq./$MJ_{biodiesel}$ (Pleanjai and Gheewala [103]). In general, it can be observed that the biodiesel production from soybean has a much greater acidification impact than the biodiesel production from palm oil.

In general, the agricultural stage presented the highest contribution to ACP environmental impact due to extensive use of fertilizers and chemicals (herbicides and insecticedes). The base case of Costa [99] reported the lowest acidification impact due to low consumption of fertilizers. The high values of ACP observed in Pleanjai and Gheewala [103] correspond to the large transportation distances between the palm oil plantation and the factory, in addition to the fact that this transport is inefficient. The high contributions of the crushing and refining stage to this environmental impact category found in Cavalett and Ortega [95]; Tsoutsos et al. [96]; Pradhan et al. [97] and Carraretto et al. [98] correspond to the fossil fuels consumption in these steps.

The reported result by the Huo et al. [134] to ACP for biodiesel production from soybean was 1.42E−3 kg SO_2-eq./$MJ_{biodiesel}$. Silalertruksa and Gheewala [135] reported ACP values for biodiesel pro duction from palm oil of 5.50E−5 kg SO_2-eq./$MJ_{biodiesel}$.

4.2.1.5. Eutrophication potential. Fig. 13 illustrates the impacts related to the ETP of biodiesel production. Note that the agricultural stage shows the major individual values of contribution to this environmental impact category. The ETP of biodiesel from soybean in these studies ranges from 8.23E−6 kg PO_4^{-3}-eq./$MJ_{biodiesel}$ (Tsoutsos et al. [96]) to 7.92E−5 kg PO_4^{-3}-eq./$MJ_{biodiesel}$ (Cavalett and Ortega [95]). The base case study of Capaz [93] presents an ETP of 6.46E−5 kg PO_4^{-3}-eq./$MJ_{biodiesel}$. The ETP of biodiesel from palm oil of the referenced studies ranges from 1.20E−5 kg PO_4^{-3}-eq./$MJ_{biodiesel}$ (Costa [99]) to 4.28E−5 kg PO_4^{-3}-eq./$MJ_{biodiesel}$ (Pleanjai and Gheewala [103]).

In general, it can be observed that the biodiesel production from soybean has a greater eutrophication impact than the one of biodiesel production from palm oil. The life cycle biodiesel production from soybean has a highest contribution to eutrophication due to an

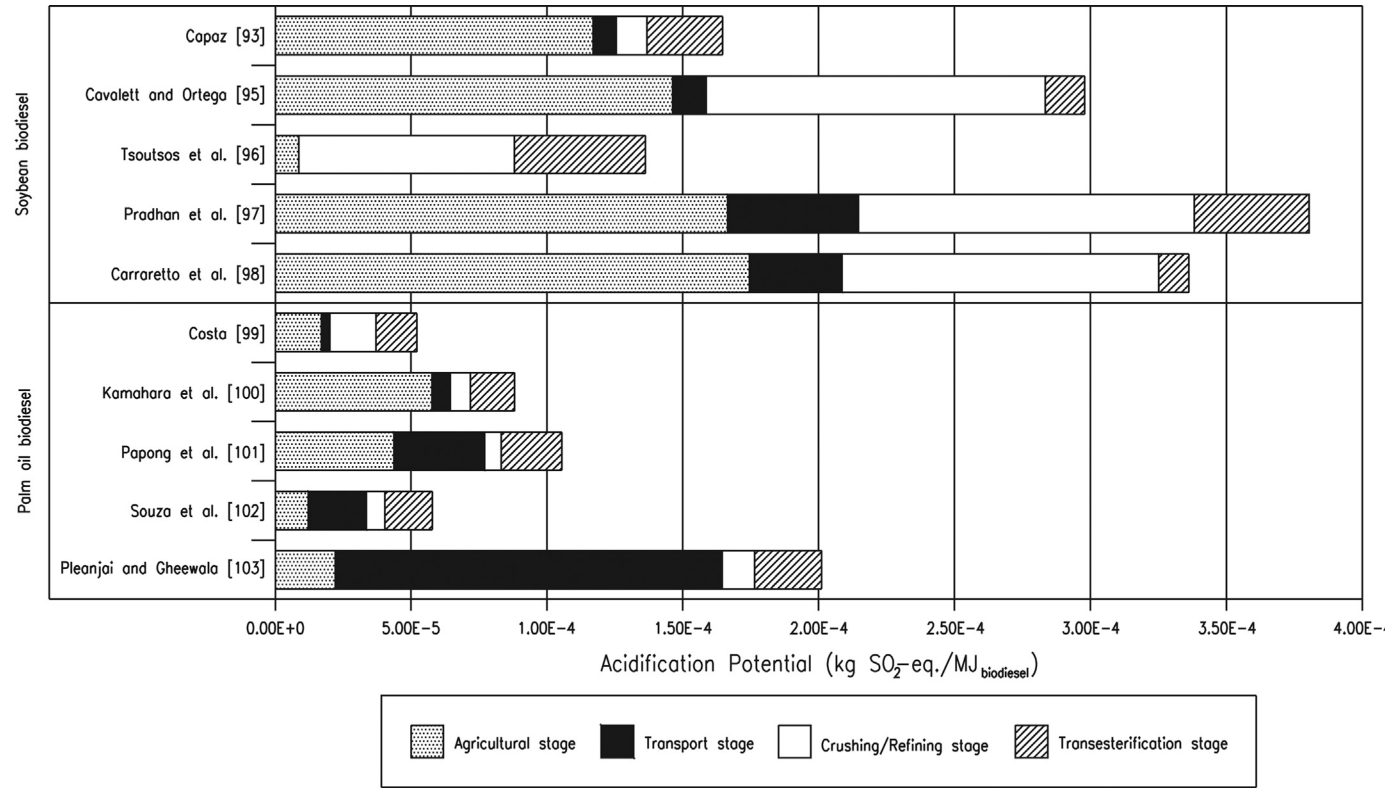


Fig. 12. ACP in life cycle of biodiesel production.

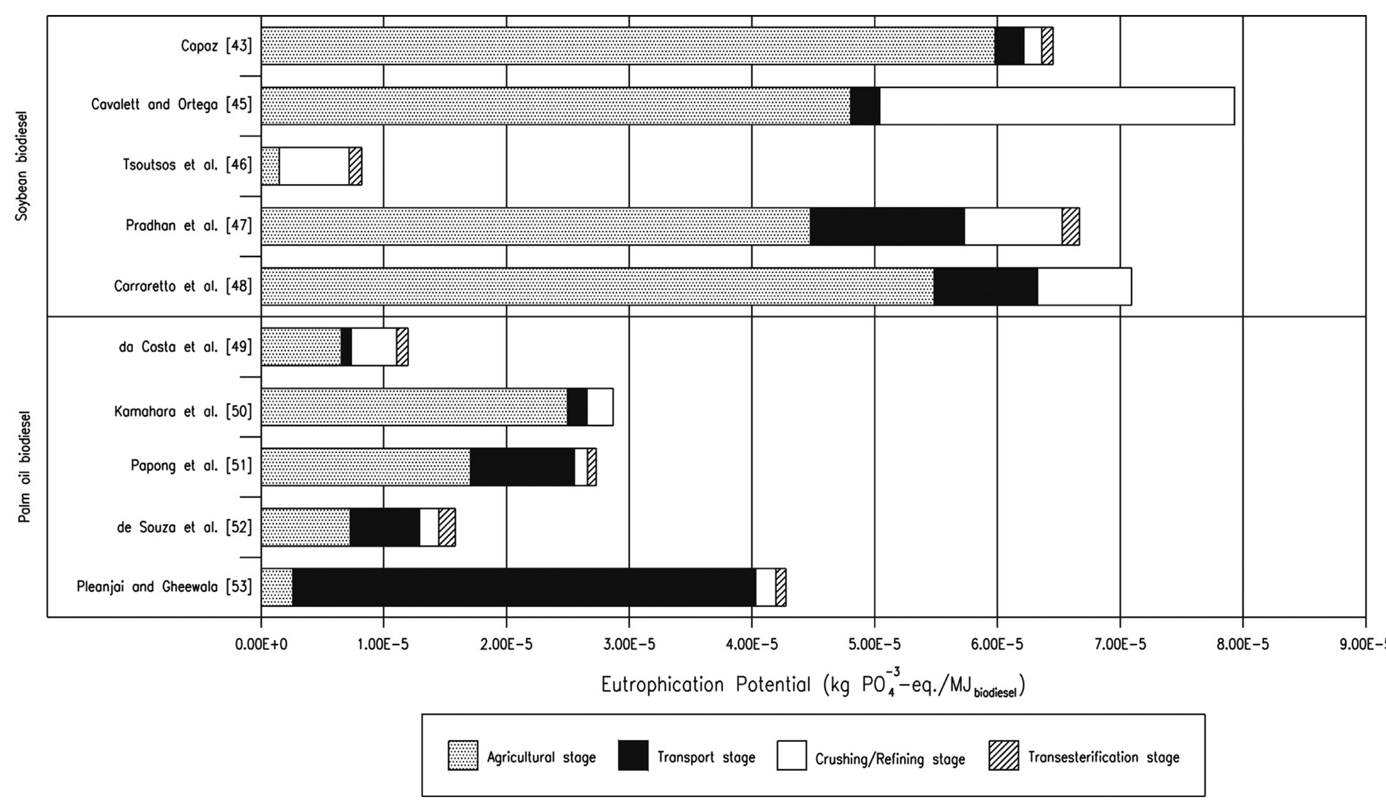


Fig. 13. ETP in life cycle of biodiesel production.

extensive use of fertilizers containing nitrogen (urea) and phosphate; in contrast, the palm oil biodiesel production has low eutrophication impacts, except in the values reported by Pleanjai and Gheewala [103], because of the high contribution of the transport stage.

Huo et al. [134] reported value of ETP environmental impact of 3.15E − 4 kg PO_4^{-3}-eq./$MJ_{biodiesel}$ for biodiesel production from soybean. The result of HTP by Silalertruksa and Gheewala [135] for biodiesel production from palm oil was 1.41E − 5 kg PO_4^{-3}-eq./$MJ_{biodiesel}$.

4.3. Life cycle energy assessment

In the LCEA of the biofuels produced in different systems the influence of the characteristics of the raw material, the process productivity and the use of co-products in the process are highlighted. The energy flows through ethanol and biodiesel production from soybean oil and palm oil will be also discussed.

4.3.1. Ethanol

The ethanol production system from sugarcane is characterized for high agricultural yields. Capaz [93] and Macedo et al. [94] presented average yields from the Center-South region of Brazil. Table 7 shows the LCEA for ethanol production. The intensification of the mechanization results in an increase of diesel consumption.

The contribution of fertilizers is lower in scenario 2 in Capaz [93] and Macedo et al. [94] due to the use of stillage and filter cake as fertilizers of sugarcane. It is known that the yield of the process of ethanol production is closely linked to the sucrose concentration in sugarcane. Thus, the data relating to varieties considered in Capaz [93] gave values of sucrose content (pol) and bagasse next to 14.26% and 12.79%, respectively, giving a yield 86.5$L_{ethanol}$/tc and the implementation of a cogeneration process with a steam cycles at 2.2 MPa, which allows to reach 54.0 MJ/tc of electricity.

Macedo et al. [94] just considered the generation of surplus bagasse, which was evaluated by its LHV (7.50 MJ/kg). The average difference in the industrial stage between the studies shows how the use co-products and the industrial yield impact the final results. In ethanol production 2.85 kJ of energy input are required to convert sugarcane into 1.0 MJ of ethanol. In this case, the chemical inputs, of sulfur, cyclohexane and lime are associated to more than 80% of energy consumption at the industrial processing stage.

This percentage could suffer a decline when the inputs for equipment and buildings are accounted, as done in Macedo et al. [50]; Boddey et al. [136]; Seabra [137]; Coelho et al. [138]; Oliveira et al. [139]; Pimentel and Patzek [140]; Nogueira [141]. The scale of the facility considered induces deviations in the results; however both studies considered an autonomous plant of 120,000 L/day, which explains the closeness of the values. In both studies, the values of the co-products generated were provided by the Sugarcane Technology Center (CTC), and corresponding to the average of mills in the São Paulo State. The Mill's energy self sufficiency is always considered [142]. Moreover, there are several options to reduce the land demand for ethanol production, increase the environmental benefits and increase the overall NER of ethanol production [142–146].

For the reasons discussed above, the indicators of the production system of ethanol were higher (Table 8). In Capaz [93] and Macedo et al. [94] scenario 2 higher values were found due to technological improvements. It will not be possible to compare the NER of ethanol production of Capaz [93] and Macedo et al. [94] with the studies of Luo et al. [131] and Cavalett et al. [132] because the latest did not assess the energy balances.

Table 7
LCEA of ethanol production from sugarcane in Brazil.

Parameter	Capaz [93] – scenario 1	Capaz [93] – scenario 2	Macedo et al. [94] – scenario 1	Macedo et al. [94] – scenario 2
Input ($kJ/MJ_{ethanol}$)	103.33	101.66	92.37	78.12
Agricultural stage	80.13	78.47	67.11	57.60
Fertilizers	30.03	18.36	34.61	27.40
Chemical application	10.30	10.30	9.99	9.36
Diesel	37.28	47.30	19.81	18.56
Electricity	0.00	0.00	0.00	0.00
Other fuels	0.00	0.00	0.00	0.00
Seeds	2.51	2.50	2.69	2.28
Transportation stage	**20.28**	**20.28**	**22.35**	**17.79**
Industrial processing stage	**2.92**	**2.92**	**2.92**	**2.73**
Diesel	0.00	0.00	0.00	0.00
Chemical	2.55	2.55	2.55	2.39
Electricity	0.00	0.00	0.00	0.00
Lubricants	0.37	0.37	0.37	0.35
Outputs ($kJ/MJ_{ethanol}$)	**1176.54**	**1176.54**	**1087.78**	**1154.25**
Ethanol	1000.00	1000.00	1000.00	1000.00
Co-products	176.54	176.54	87.78	154.25

4.3.2. Biodiesel

4.3.2.1. Soybean. According to Table 9, the agricultural stage of biodiesel production from soybean is responsible for higher energy consumption, except in Tsoutsos et al. [96], who did not account the contribution of phosphorus, potassium, seeds and diesel required in the agricultural operations. Cavalett and Ortega [95] presented the highest energy demand due to the intense use of pesticides and electricity for the tillage operation systems. On the other hand, both, Capaz [93] and Pradhan et al. [97] studies, presented lower energy consumptions associated to fertilization because considered the biological fixation of nitrogen in the soybean roots.

The intense agricultural mechanization in the case studies of Cavalett and Ortega [95]; Pradhan et al. [97]; Carraretto et al. [98] give a high consumption of diesel, of 140.0; 55.0 and 65.0 L/ha, respectively. In this stage, Pradhan et al. [97] considered an intense use of gasoline, natural gas and propane of about 22 L/ha; 2.45 L/ha and 748 L/ha, respectively.

In Pradhan et al. [97], a distance of 80 km was considered, making this stage responsible for about 6% of the whole energy demand, similar to the 5% observed in Carraretto et al. [98]. In turn, in Capaz [93] 20.0 km was considered, corresponding to 2%. The transportation distance of Tsoutsos et al. [96] was not accounted due to lack of data.

The energy input in the industrial stage varied considerably in the evaluated studies, depending directly on the different dimensions of the facilities and the fuels used to produce steam for the process, which is the major energy expenditure in this stage. Tsoutsos et al. [96] and Pradhan et al. [97] have not considered the use of hexane in the extraction of soybean oil, and Capaz [93] considered the use of renewable fuel to produce steam at about 0.35 kg of wood/kg_{oil} processed.

Table 8
NER for ethanol production.

Studies	Input ($kJ/MJ_{ethanol}$)	Output ($kJ/MJ_{ethanol}$)	NER_{total}	$NER_{ethanol}$	$NER_{allocated}$
Capaz [93] – scenario 1	101.83	1142.56	11.22	9.82	14.27
Capaz [93] – scenario 2	100.44	1174.40	11.69	9.96	14.47
Macedo et al. [94] – scenario 1	92.37	1087.78	11.78	10.83	14.44
Macedo et al. [94] – scenario 2	78.12	1154.25	14.77	17.36	20.31
Average			**12.37**	**11.99**	**15.87**

Table 9
LCEA of biodiesel produced from soybean oil.

Parameters	Capaz [93]	Cavalett and Ortega [95]	Tsoutsos et al. [96]	Pradhan et al. [97]	Carraretto et al. [98]
Input (kJ/MJ$_{biodiesel}$)	**648.11**	**1023.75**	**861.88**	**647.71**	**740.44**
Agricultural stage	**280.01**	**501.51**	**224.24**	**210.45**	**398.17**
Fertilizers	64.11	77.38	157.74	32.31	199.72
Chemical application	61.20	153.63	66.51	28.88	20.39
Diesel	78.06	123.44	0.00	79.73	174.56
Electricity	0.00	50.47	0.00	7.79	0.00
Other fuels	0.00	0.00	0.00	40.55	3.51
Seeds	76.64	96.59	0.00	21.19	0.00
Transportation stage	**10.84**	**10.17**	**0.00**	**36.83**	**37.92**
Crushing and refining stage	**181.98**	**381.31**	**400.28**	**212.50**	**194.86**
Diesel	0.00	114.62	0.00	0.00	0.00
Chemical	6.31	6.32	0.00	0.00	5.90
Electricity	17.85	35.05	85.76	69.48	188.88
Other fuels[a]	157.82	225.31	314.52	143.02	0.07
Transesterification stage	**175.29**	**130.75**	**237.35**	**187.93**	**109.49**
Diesel	0.00	0.00	0.00	0.00	0.00
Chemical	135.10	130.57	220.03	122.77	109.49
Electricity	1.80	0.19	17.33	11.13	0.00
Other fuels[a]	38.39	0.00	0.00	54.03	0.00
Output (kJ/MJ$_{biodiesel}$)	**2702.76**	**2486.36**	**1000.00**	**2881.83**	**1629.47**
Biodiesel	1000.00	1000.00	1000.00	1000.00	1000.00
Co-products	1702.76	1486.36	0.00	1881.83	629.47

[a] Lubricants are considered.

Table 10
NER for biodiesel production from soybean.

Studies	Input (kJ/MJ$_{biodiesel}$)	Output (kJ/MJ$_{biodiesel}$)	NER$_{total}$	NER$_{biodiesel}$	NER$_{allocated}$
Capaz [93]	648.11	2702.76	4.17	1.54	8.57
Cavalett and Ortega [95]	1023.75	2486.36	2.43	0.98	4.80
Tsoutsos et al. [96]	861.88	1000.00	1.16	1.16	1.16
Pradhan et al. [97]	647.71	2881.83	4.45	1.54	9.08
Carraretto et al. [98]	740.36	1629.47	2.20	1.35	3.44
Average			**2.88**	**1.31**	**5.41**

In the transesterification stage, the methanol represents an 80% of the energy input in this stage in actual conditions, that tends to shift the chemical equilibrium and accelerate the reaction [147].

Cavalett and Ortega [95]; Tsoutsos et. al [96] and Carraretto et al. [98] have not recorded the fuel input in the steam boilers. Pradhan et al. [97] used natural gas for this purpose, the electricity consumption was significant, reaching 10% of the energy consumed at this stage to drive the pumps, centrifuges, and mixers. The total energy input was estimated based on the fossil fuel share in each input presented by those authors.

Regarding to co-products generation in the process, the production of soybean meal is significant in the oil extraction stage. This co-product, commonly used as animal feed, represents more than half the total mass production in the biodiesel production process, in the transesterification stage 0.15 kg of glycerol was generated per kg of biodiesel. This co-product is commonly used in the pharmaceutical or cosmetic industry; in Tsoutsos et al. [96] the generation co-products, was not considered, what impacted in the final indicators.

Table 10 shows the energy indicators of biodiesel production from soybean. The average of the NER$_{total}$ for the biodiesel production chain from soybean oil was 2.88, ranging from 1.16 (Tsoutsos et al. [96]) to 4.45 (Pradhan et al. [97]). It is worthwhile to observe that these indicators are different from the values presented in the original studies, due to methodological issues of accounting of direct energy and indirect energy in inputs.

The energy valuation of co-products, particularly soybean meal, affects the obtained results among the studies and calculated indicators. From this point of view the study of Tsoutsos et al. [96] presented the lowest indicators basically because they did not consider the generation of co-products. An opposite approach was the one of Capaz [93], which considered the generation of 5.66 kg of soybean meal/kg$_{biodiesel}$, resulting in a NER$_{total}$ of 4.21. The determination of NER$_{allocated}$ considering the mass nearly doubles the value of indicators due to the high mass fraction of soybean meal in soybean. It will not be possible to compare the NER of soybean biodiesel production of Hou et al. [134] because this study did not assess the energy balances.

Even though the based method of the energy content can be applied to the energy analysis of biodiesel production from soybean, the application did not reflect neither the use of individual products nor the energy use and emissions of producing individual products. This situation indicates a relevant limitation of the energy based analysis, from the moment that the co-products are not necessarily used as energy source its valuation, according to their heating value, can result in a wrong analysis and encourages misinterpretations.

4.3.2.2. Palm oil. In general, the biodiesel production system from palm oil (Table 11) is characterized by relative lower inputs in comparison with soybean biodiesel route, due to the high yield of the crop and intensive use of co-products in the process. In all studies the use of residual PPF and PKS in cogeneration systems was considered to supply steam and electricity to the extraction and/or transesterification process, reducing remarkably the external energy demand. In soybean biodiesel production, 442.34 kJ are required to convert the soybean oil in 1.0 MJ of biodiesel, in palm oil biodiesel production it's only 188.69 kJ.

Logistics in bioenergy systems have a great impact over the energy performance of the production chain. Particularly, in the studies in Thailand, the consumption associated with FFB transportation to the extraction plant and the CPO transportation to transesterification facility is significant, due to the distance of more than 1500 km in Pleanjai and Gheewala [103], who estimated a value close to 130.0 kJ/MJ$_{biodiesel}$ in this stage. In the

Table 11
LCEA of biodiesel produced from palm oil.

Parameters	Costa [99]	Kamahara et al. [100]	Papong et al. [101]	Souza et al. [102]	Pleanjai and Gheewala [103]
Input (kJ/MJ$_{biodiesel}$)	**239.01**	**335.66**	**389.23**	**245.18**	**412.27**
Agricultural stage	**90.75**	**81.23**	**133.03**	**59.33**	**119.75**
Fertilizers	64.65	74.06	104.98	47.57	99.57
Chemical application[a]	8.55	7.18	13.93	11.69	18.41
Diesel	3.77	0.00	14.13	0.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00
Other fuels[b]	9.87	0.00	0.00	0.00	0.00
Seeds	3.91	0.00	0.00	0.07	1.76
Transportation stage	**0.83**	**5.86**	**31.14**	**25.89**	**130.07**
Crushing and refining stage	**29.02**	**7.67**	**4.20**	**6.49**	**6.56**
Diesel	7.13	7.67	2.29	6.12	5.77
Chemical	0.00	0.00	0.00	0.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00
Other fuels[a]	21.89	0.00	1.92	0.37	0.79
Transesterification stage	**118.42**	**240.89**	**220.85**	**153.47**	**155.89**
Diesel	0.00	0.00	0.00	0.00	0.00
Chemical	109.30	152.92	176.39	106.63	148.01
Electricity	9.12	87.97	0.12	46.84	7.88
Other fuels[b]	0.00	0.00	44.33	0.00	0.00
Output (kJ/MJ$_{biodiesel}$)	**1052.87**	**1110.63**	**1464.43**	**1074.96**	**1478.89**
Biofuel	1000.00	1000.00	1000.00	1000.00	1000.00
Co-products	52.87	110.63	464.43	74.96	478.89

[a] Boron and magnesium are considered.
[b] Lubricants are considered.

Table 12
NER of biodiesel production from palm oil.

Studies	Input (kJ/MJ$_{biodiesel}$)	Output (kJ/MJ$_{biodiesel}$)	NER$_{total}$	NER$_{biodiesel}$	NER$_{allocated}$
Costa [99]	239.01	1052.87	4.41	4.18	4.67
Kamahara et al. [100]	335.66	1110.63	3.31	2.98	3.48
Papong et al. [101]	389.23	1464.43	3.76	2.57	6.69
de Souza et al. [102]	245.18	1074.96	4.38	4.08	15.43
Pleanjai and Gheewala [103]	412.27	1478.89	3.59	2.43	4.88
Average			**3.89**	**3.25**	**7.03**

opposite side Costa et al. [99] and Kamahara et al. [100] presented lower values because the shorter distance between plantation and industry, about 20 km and 8 km, respectively.

In the transesterification stage, the energy cost corresponding to the use of methanol is the higher energy inputs at this stage. Kamahara et al. [100] and Papong et al. [101] appointed higher energy consumption in this stage due to the use of electricity from the grid and fuel oil.

The energy output of the whole biodiesel production system, presented lower values for palm oil (an average of 1200 kJ/MJ$_{biodiesel}$) in comparison to soybean biodiesel, mainly due to the use of co-products in the system. In Souza et al. [102] the glycerol generation was not accounted and it was assumed the generation of surplus electricity from residual PPF, PKS and biogas obtained from the POME, considering 68% boiler efficiency. In this study it was found that 1.0 t of FFB yields of 14.0 m^3 POME or 25 kWh of electricity, as an average.

Table 12 shows the energy indicators of biodiesel production from palm oil. The agricultural yield and the use of co-products in the process guarantee an average of NER$_{total}$ (3.89), greater than the one observed in the soybean case (2.88). In Souza et al. [102] the generation of electricity surplus with residual PPF, PKS and biogas were accounted. On the other hand, Papong et al. [101] considered the output of these residues without processing. It is interesting to comment that when co-products are used in the biodiesel process, NER$_{biofuel}$ and NER$_{allocated}$ are closer to NER$_{total}$, observed in palm biodiesel cases, but different in soybean biodiesel chains.

Silalertruksa and Gheewala [135] show a NER for palm oil biodiesel production of 2.07, considering just the biodiesel production (without co-products); while the NER of biodiesel considering them co-products are 4.30. The greater value of NER of biodiesel plus co-products is due to the EFB, which is currently being dumped in the plantation or in the mill, being used as biomass fuel. Fig. 14 shows the calculated results of NER$_{biofuel}$ and Fig. 15 shows the calculated results of NER$_{total}$ for all the evaluated studies.

5. Conclusions

The world population, requirements for food and feed permanently increases. This creates growing demands for production and consumption of biofuels in the last years. While high oil prices favored this growth, it was also supported and drove by policies such as mandates, targets and subsidies catering to energy security and climate change considerations.

The study's main task, to make a serious, multidirectional and holistic evaluation and comparison of the environmental life cycle impacts, complemented with an energy balance of two most used biofuels: ethanol and biodiesel, from three different crops: sugarcane, soybeans and palm oil tree oils respectively. Moreover, this paper offers a novel, original and exhaustive comparison of the environmental impacts and the energetic potential of two of the most extended used biofuels.

The results, in the praxis, confirmed that the methodology used in the scientific work, reported in the paper, was not only the most appropriate one, but also gives a wide view, ensuring a solid meta-analysis. The combination of the data available in Brazil though the CML 2 Baseline 2000, with the selected previous studies, using the tool of the Simapro 7.0.1 software, upon which the meta-analysis was based, was a fortunate decision. The ecological damages were quantified in five categories of environmental impact potentials:

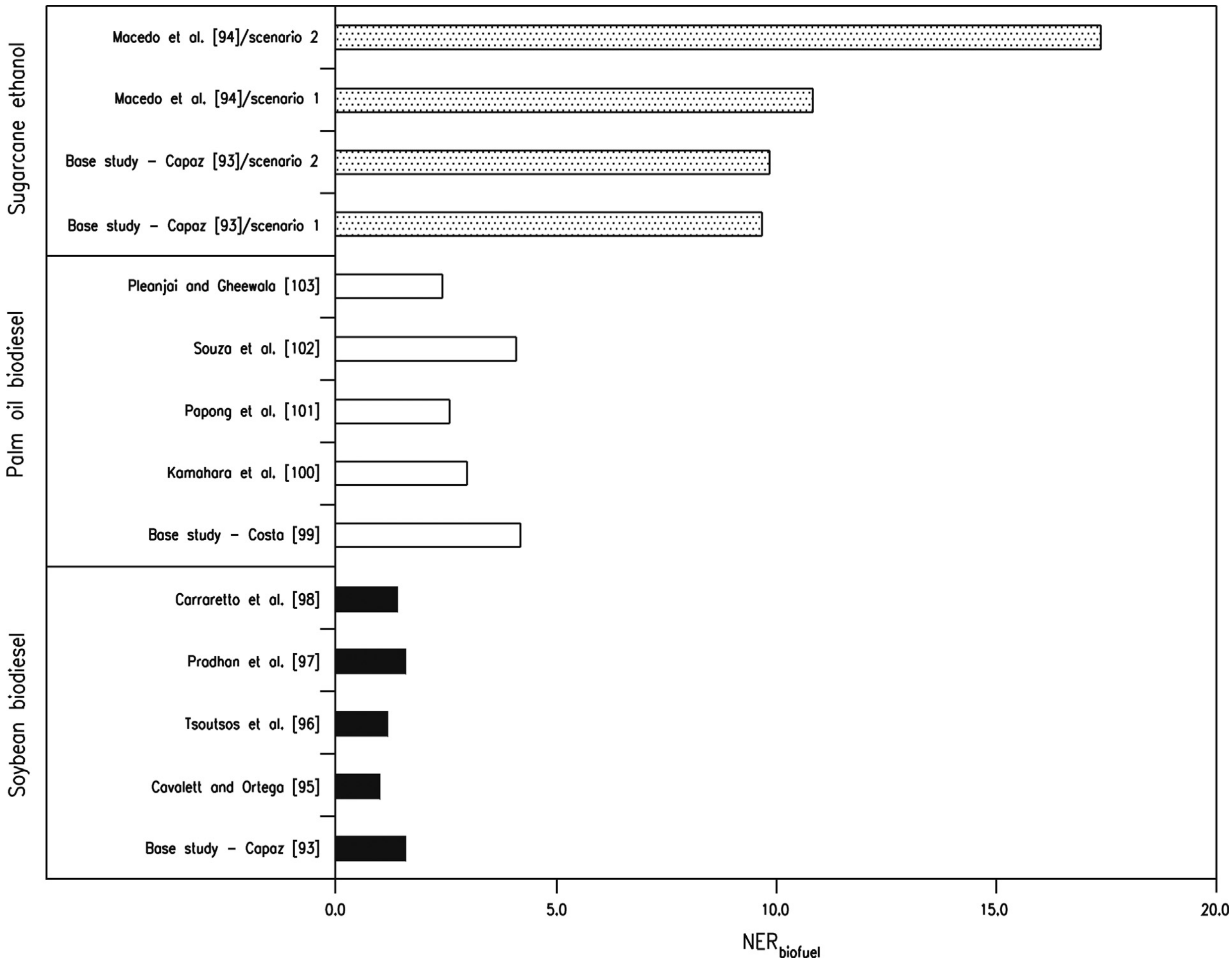


Fig. 14. Comparison between $NER_{biofuel}$ results for sugarcane ethanol, soybean biodiesel and palm oil biodiesel of the evaluated studies.

ADP, GWP, HTP, ACP and ETP. The application of LCA as a tool during the decision making to determine which technology is the most appropriate for the production of biofuels from an environmental point of view. Results on environmental impact evaluation show considered differences in the results of analyzed studies.

On the other hand, the information organized in the this paper, identifying the kind, intensity and interrelations of aggressions, the environment has suffered several detrimental effects, as a consequence of the production of the so called "biofuels". Those results are a useful reference for future scientific works related to the development of new technologies and/or an effective adequateness of the existing ones, for the production of biofuels, with higher efficiency, effectiveness and safety, looking for a true sustainability. The study is complemented with the consideration, in each case, of an extended boundary, which facilitates a detailed evaluation of the influence and environmental impact, of each significant technological step, required for the production of the analyzed biofuels.

It is significant, in all cases, the major role of the transportation of the crops, from the field to the factory, in the total environmental impact, making the distance a limiting factor and showing clearly the need to give priority to the development of ways and means to reduce it. In this cradle-to-gate LCA carried out was observed that the consumption of fossil fuels is associated with several impacts, such as, ADP or GWP, that indicates the necessity to reduce it in logistic and industrial stages, adopting other alternatives. LCA pointed out the fact that the environmental impact potentials of ethanol and biodiesel vary in a wide range of the analyzed impact categories.

The reported results confirm that the use of the co-products and residues of the production of the biofuels, for electrical and thermal energy, through cogeneration, to be used in the processes, improve the ecological and economical benefits, increasing the appeal of the ethanol and biodiesel alternative. The use of co-products in process, to generate steam and electricity, results in good indicators because it decreases or cancels the external dependence of fossil fuels and electricity, and allows, in some cases, the supply of renewable electricity or fuels to use in other process. This practice could, in some cases, represent the satisfaction of 85 to 95% of the total energy demand.

A wide range of high added value products such as enzymes, organic acids, biopolymers, electricity, and molecules for food and pharmaceutical industries could be obtained upgrading of industrial co-products of biofuels production. Further works are require to have a more realistic consideration of the co-products and biomass valorization contribution to LCA indicators. The LHV approach for soybean meal, glycerol and lignocellulosic residues, such as, bagasse and sugarcane trash for ethanol production and EFB, PKS, PPF and POME for palm oil biodiesel production have been used in real industrial applications process on animal feed and surplus electricity generation.

In ethanol production the sugarcane trash represents 30% of total primary energy of the sugarcane as a crop and it has characteristics very similar to the widely sugarcane bagasse, which makes it a very good fuel to supplement bagasse for surplus electricity. In biodiesel production glycerol is recognized as a waste with numerous applications and its bioconversion into high-value added metabolic products offers a significant

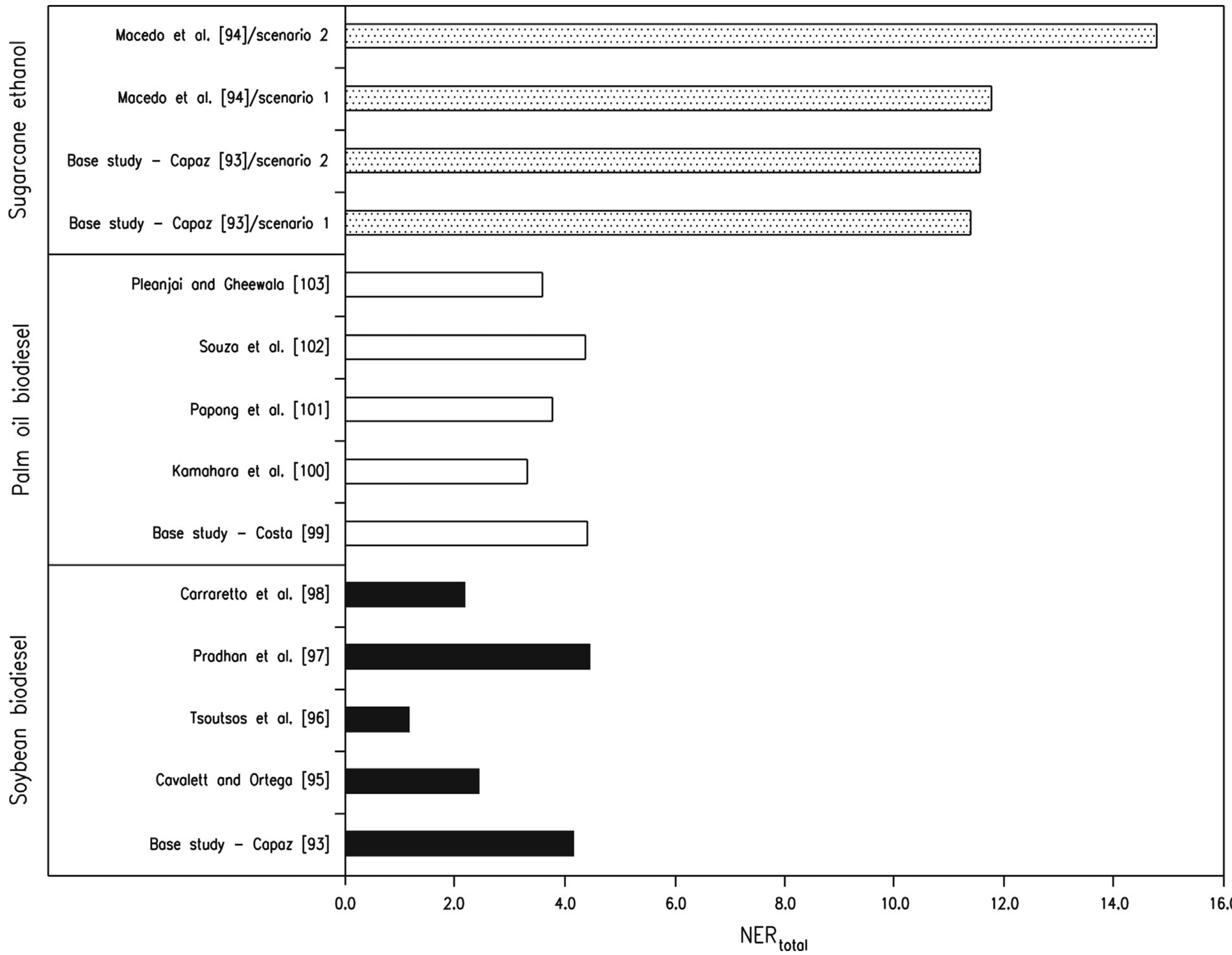


Fig. 15. Comparison between NER_{total} results for sugarcane ethanol, soybean biodiesel and palm oil biodiesel of the evaluated studies.

advantage in the efficient management of biodiesel production wastes and the development of sustainable technologies.

Based on paper data it is possible to highlight the main potential indicators to improve the environmental and energy performance of evaluated biofuels life cycle, such as: reductions in fossil fuel inputs in the agricultural stage, a widespread and efficient utilization of wastes for agriculture purposes, substitution of fossil inputs by renewable ones and increase of agricultural yields and industrial recovery efficiency.

In relation to net energy balance, the NER results for evaluated biofuels show the highest value for sugarcane ethanol followed by palm oil and finally soybean biodiesel. The ethanol presents better indicators than biodiesel, essentially because of its higher efficiency and productivity. In fact, the excellent performance of sugarcane as a solar energy converter is the basis of Brazilian ethanol sustainability. Agricultural productivity differences and fossil input in vegetable oils transesterification could explain these results. From the point of view of the agriculture, the reuse of the nitrogen, phosphorus and potassium ions as fertilizers, by the fertirrigation with stillage, not only protect the soils, but also represents a net economical input. In some case is possible to find remarkable differences in the results from one to another biofuel, as is the case of the biodiesel from soybeans and palm oil; in the first case 442.34 kJ are required to convert the soybean oil in 1.0 kJ of biodiesel, in the second one only 188.69 kJ are required.

This fact indicate the need of very serious analysis, considering in every case, the important interrelations, before a decision is made; always having in mind, when considering this complex systems, the Aristotelian holistic principle that: “The whole is grater that the addition of its parts”. From all the above considerations, it is possible to conclude that there is still a long way to go in R&D in the complex, appealing and demanding world of the biological based fuels.

Brazilian biofuel programs demonstrate the feasibility of a sustainable way for renewable fuels utilization. The Brazilian government is funding and encouraging academic and industrial R&D projects, and is also creating several research institutions, aimed at improving the sustainability of domestic biofuels. Moreover, Brazil offers an excellent opportunity to improve the energy performance of the crops to biofuels production, the economics and the sustainability of biofuels production.

Acknowledgments

We wish to thank the Brazilian National Research and Development Council (CNPq). The Research Support Foundation of the Minas Gerais State (FAPEMIG) and the Coordinating Body for the Improvement of Postgraduate Studies in Higher Education (CAPES) for the funding of R&D projects. The support of graduate students and the production grants that allowed the accomplishment of the research projects whose results are included in this paper.

References

[1] Eisentraut A. Sustainable production of second-generation biofuels. Potential and perspectives in major economies and developing countries. International

Energy Agency (IEA), Paris, France, February 2010. Available at: 〈http://www.iea.org/publications/freepublications/publication/biofuels_exec_summary.pdf〉. [accessed 02.01.13.].
[2] Nogueira LAH, Moreira JR, Schuchardt U, Goldemberg J. The rationality of biofuels. Energy Policy 2013;61:595–8.
[3] Malça J, Freire F. Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues. Renew Sustain Energy Rev 2011;15(1):338–51.
[4] Nogueira LAH. Does biodiesel make sense? Energy 2011;36(6):3659–66.
[5] Percival Zhang Y-H. What is vital (and not vital) to advance economically-competitive biofuels production. Process Biochem 2011;46(11):2091–110.
[6] Smyth BM, Gallachóir BPÓ, Korres NE, Murphy JD. Can we meet targets for biofuels and renewable energy in transport given the constraints imposed by policy in agriculture and energy? J Clean Prod 2010;18(16–17):1671–85.
[7] Koçar G, Civaş N. An overview of biofuels from energy crops: current status and future prospects. Renew Sustain Energy Rev 2013;28:900–16.
[8] Puri M, Abraham RE, Barrow CJ. Biofuel production: Prospects, challenges and feedstock in Australia. Renew Sustain Energy Rev 2012;16(8):6022–31.
[9] Limayem A, Ricke SC. Lignocellulosic biomass for bioethanol production: current perspectives, potential issues and future prospects. Prog Energy Combust Sci 2012;38(4):449–67.
[10] Escobar JCP, Lora EES, Venturini OJ, Yáñez EE, Castillo EF, Almazán O. Biofuels: environment, technology and food security. Renew Sustain Energy Rev 2009;13(6–7):1275–87.
[11] Jin C, Yao M, Liu H, Lee CF, Ji J. Progress in the production and application of n-butanol as a biofuel. Renew Sustain Energy Rev 2011;15(8):4080–106.
[12] Rabelo SC, Carrere H, Maciel Filho R, Costa AC. Production of bioethanol, methane and heat from sugarcane bagasse in a biorefinery concept. Bioresour Technol 2011;102(17):7887–95.
[13] Reichling JP, Kulacki FA. Comparative analysis of Fischer–Tropsch and integrated gasification combined cycle biomass utilization. Energy 2011;36 (11):6529–35.
[14] Renó MLG, Lora EES, Escobar JCP, Venturini OJ, Buchgeister J, Almazán O. ALCA (life cycle assessment) of the methanol production from sugarcane bagasse. Energy 2011;36(6):3716–26.
[15] Qureshi N, Saha BC, Dien B, Hector RE, Cotta MA. Production of butanol (a biofuel) from agricultural residues: Part I – use of barley straw hydrolysate. Biomass Bioenergy 2010;34(4):559–65.
[16] Lv Y, Wang T, Wu C, Ma L, Zhou Y. Scale study of direct synthesis of dimethyl ether from biomass synthesis gas. Biotechnol Adv 2009;27(5):551–4.
[17] Salomon KR, Lora EES. Estimate of the electric energy generation potential for different sources of biogas in Brazil. Biomass Bioenergy 2009;33(9):1101–7.
[18] Capaz RS, Carvalho CVB, Nogueira LAH. Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil. Appl Energy 2013;102(2):220–8.
[19] Mussatto SI, Dragone G, Guimarães PMR, Silva JPA, Carneiro LM, Roberto IC, et al. Technological trends, global market, and challenges of bio-ethanol production. Biotechnol Adv 2010;28(6):817–30.
[20] Sorda G, Banse M, Kemfert C. An overview of biofuel policies across the world. Energy Policy 2010;38(11):6977–88.
[21] Nogueira LAH, Capaz RS. Biofuels in Brazil: evolution, achievements and perspectives on food security. Global Food Secur 2013;2(2):117–25.
[22] CGEE. Strategic studies and management. sustainability of sugarcane bioenergy: updated edition. isbn:978-85-60755-47-9. Brasília:CGEE, 2012. 360p.
[23] INBIOM. Innovation network for biomass. Market description. The environmental technology and bioenergy in Brazil: with focus on São Paulo, Paraná and Rio de Janeiro regions. Agro Business Park A/S. Cooperation with DJF, Agrotech, KU and Risø DTU. Tjele, October, 2011, 43p.
[24] Valdes C. Brazil's ethanol industry: looking forward. United States Department of Agriculture (USDA). Report from the Economic Research Service/USDA/BIO-02. 46p., June 2011. Available at: 〈http://www.ers.usda.gov/media/126865/bio02.pdf〉. [accessed 04.01.13].
[25] Kumar N, Varun, Chauhan SR. Performance and emission characteristics of biodiesel from different origins: a review. Renew Sustain Energy Rev 2013;21:633–58.
[26] Milazzo MF, Spina FS, Primerano P, Bart JCJ. Soy biodiesel pathways: global prospects. Renew Sustain Energy Rev 2013;26:579–624.
[27] Gerbens-Leenes PW, van Lienden AR, Hoekstra AY. van der Meer ThH. Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. Global Environ Change 2012;22 (3):764–75.
[28] Mekhilef S, Siga S, Saidur R. A review on palm oil biodiesel as a source of renewable fuel. Renew Sustain Energy Rev 2011;15(4):1937–49.
[29] Yusuf NNAN, Kamarudin SK, Yaakub Z. Overview on the current trends in biodiesel production. Energy Convers Manag 2011;52(7):2741–51.
[30] Balat M, Balat H. Progress in biodiesel processing. Appl Energy 2010;87 (6):1815–35.
[31] Demirbas A. Political, economic and environmental impacts of biofuels: a review. Appl Energy 2009;86(Supplement 1):S108–17.
[32] Castanheira EG, Grisoli R, Freire F, Pecora V, Coelho ST. Environmental sustainability of biodiesel in Brazil. Energy Policy 2014;65:680–91.
[33] César AS, Batalha MO, Zopelari ALMS. Oil palm biodiesel: Brazil's main challenges. Energy 2013;60:485–91.
[34] Oberling DF, Obermaier M, Sklo A, la Rovere EL. Investments of oil majors in liquid biofuels: the role of diversification, integration and technological lock-ins. Biomass Bioenergy 2012;46:270–81.
[35] Simões AF, Kligerman DC, la Rovere EL, Maroun MR, Barata M, Obermaier M. Enhancing adaptive capacity to climate change: the case of smallholder farmers in the Brazilian semi-arid region. Environ Sci Policy 2010;13 (8):801–8.
[36] Maroun MR, la Rovere EL. Ethanol and food production by family smallholdings in rural Brazil: economic and socio-environmental analysis of micro distilleries in the State of Rio Grande do Sul. Biomass Bioenergy 2014;63:140–55.
[37] van Eijck J, Romijn H, Balkema A, Faaij A. Global experience with jatropha cultivation for bioenergy: an assessment of socio-economic and environmental aspects. Renew Sustain Energy Rev 2014;32:869–89.
[38] Mohr A, Raman S. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Energy Policy 2013;63:114–22.
[39] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials – methodological lessons from review of state of the art bioenergy potential assessments. Renew Sustain Energy Rev 2012;16(9):6598–630.
[40] Goldemberg J, Coelho ST, Guardabassi P. The sustainability of ethanol production from sugarcane. Energy Policy 2008;36(6):2086–97.
[41] Silva DAL, Delai I, Montes MLD, Ometto AR. Life cycle assessment of the bagasse electricity generation in Brazil. Renew Sustain Energy Rev 2014;32:532–47.
[42] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Sci 2001;37(1):52–68.
[43] Lora EES, Andrade RV. Biomass as energy source in Brazil. Renew Sustain Energy Rev 2009;13(4):777–88.
[44] Bertogli G, Avila-Merino A, Corazzi E, Bocci E, Naso V. Renewable energy technologies for the production of bio-fuels perspectives and appropriate technologies for african countries. Trieste: International Centre for Science and High Technology (ICS) and United Nations Industrial Development Organization (UNIDO). ICS-UNIDO; 2008; 120.
[45] Bordonal RO, Figueiredo EB, Aguiar DA, Adami M, Rudorff BFT, La Scala N. Greenhouse gas mitigation potential from Green harvested sugarcane scenarios in São Paulo State, Brazil. Biomass Bioenergy 2013;59:195–207.
[46] Leal MRLV, Galdos MV, Scarpare FV, Seabra JEA, Walter A, Oliveira COF. Sugarcane straw availability, recovery and energy use: a literature review. Biomass Bioenergy 2013;53:11–9.
[47] Fortes C, Trivelin PCO, Vitti AC. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. Biomass Bioenergy 2012;42:189–98.
[48] Khatiwada D, Seabra JEA, Silveira S, Walter A. Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: methodological references in European and American regulations. Energy Policy 2012;47:384–97.
[49] Seabra JEA, Tao L, Chum HL, Macedo IC. A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering. Biomass Bioenergy 2010;34(8):1065–78.
[50] Macedo IC, Seabra JEA, Silva JEAR. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and prediction for 2020. Biomass Bioenergy 2008;32(7):582–95.
[51] Lora EES, Arrieta FRP, Carpio RC, Nogueira LAH. Clean production: efficiency and environment. Int Sugar J 2000;102(1219):343–51.
[52] Cortez LAB, Magalhães PSG, Happi J. Principais subprodutos da agroindústria Canavieira e sua valorização (The main co-products of sugarcane industry and its valorization). Rev Bras Energ (Braz J Energy) 1992;2(2):111–46 [in portuguese].
[53] Escobar JCP, Lora EES, Venturini OJ, Santos VA, Renó MLG. Cogeneration options for improving the competitiveness of a cane-based ethanol plant in Brazil. Int Sugar J 2011;113(1351):509–15.
[54] Lora EES, Zampieri M, Venturini OJ, Santos JJCS. A sugar mill cogeneration plant repowering alternatives: evaluation through the combination of thermodynamic and economic concepts. Int Sugar J 2008;110(1316):488–95.
[55] Lora EES, Zampieri M, Nogueira LAH, Leal MRLV, Cobas VM. Thermodynamic limits for the production of ethanol and electricity from sugarcane. Zuckerind (Sugar Ind) 2006;131(11):759–65.
[56] Pistore TT, Lora EES. Economic, technical and environmental assessment on cogeneration in the sugar/alcohol industry. Zuckerind (Sugar Ind) 2006;108 (1292):441–53.
[57] Seabra JEA, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. Biofuels, Bioprod Bioref 2011;5(5):519–32.
[58] Walter A, Dolzan P, Quildrán O, de Oliveira JG, da Silva C, Piacente F, et al. Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. Energy Policy 2011;39(10):5703–16.
[59] Ometto AR, Hauschild MZ, Roma WNL. Lifecycle assessment of fuel ethanol from sugarcane in Brazil. Int J Life Cycle Assess 2009;14(3):236–47.
[60] Rocha MH, Lora EES, Venturini OJ, Escobar JCP, Santos JJCS, Moura AG. Use of the life cycle assessment (LCA) for comparison of the environmental performance of four alternatives for the treatment and disposal of bioethanol stillage. Int Sugar J 2010;112(1343):611–22.
[61] Rocha MH, Lora EES, Venturini OJ. Life Cycle Analysis of different alternatives for the treatment and disposal of ethanol vinasse. Zuckerind (Sugar Ind) 2008;133(2):88–93.
[62] Lora EES, Rocha MH, Escobar JCP, Venturini OJ, Renó MLG, Almazán OO. The sugar and alcohol industry in the biofuels and cogeneration era: a paradigm change (part I). Zuckerind (Sugar Ind) 2014;139(1):28–36.

[63] Lora EES, Rocha MH, Escobar JCP, Venturini OJ, Renó MLG, Almazán OO. The sugar and alcohol industry in the biofuels and cogeneration era: a paradigm change (part II). Zuckerind (Sugar Ind) 2014;139(2):97–104.
[64] Bergmann JC, Tupinambá DD, Costa OYA, Almeida JRM, Barreto CC, Quirino BF. Biodiesel production in Brazil and alternative biomass feedstocks. Renew Sustain Energy Rev 2013;21:411–20.
[65] Mourad AL, Walter A. The energy balance of soybean biodiesel in Brazil: a case study. Biofuels, Bioprod Biorefining 2011;5(2):185–97.
[66] Yáñez EEA, Lora EES, da Costa RE, Torres EA. The energy balance in the Palm Oil-Derived Methyl Ester (PME) life cycle for the cases in Brazil and Colombia. Renew Energy 2009;34(12):2905–13.
[67] Rajaeifar MA, Ghobadian B, Safa M, Heidari MD. Energy life-cycle assessment and CO_2 emissions analysis of soybean-based biodiesel: a case study. J Clean Prod 2014;66:233–41.
[68] Lin C-Y. Strategies for promoting biodiesel use in marine vessels. Mar Policy 2013;40:90–4.
[69] Huo H, Wang M, Bloyd C, Putsche V. Life-cycle assessment of energy use and Greenhouse Gas emissions of soybean-derived biodiesel and renewable fuels. Environ Sci Technol 2009;43(3):750–6.
[70] Pradhan A, Shrestha DS, Van Gerpen J, Duffield J. The energy balance of soybean oil biodiesel production: a review of past studies. Trans Am Soc Agric Biol Eng 2008;51(1):185–94.
[71] Rodrigues TO, Caldeira-Pires A, Luz S, Frate CA. GHG balance of crude palm oil for biodiesel production in the northern region of Brasil. Renew Energy 2014;62:516–21.
[72] Hassan MNA, Jaramillo P, Griffin WM. Life cycle GHG emissions from Malaysian oil palm bioenergy development: the impact on transportation sector's energy security. Energy Policy 2011;39(5):2615–25.
[73] Lam MK, Lee KT, Mohamed AR. Life cycle assessment for the production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil. Biofuels, Bioprod Biorefining 2009;3(6):601–12.
[74] Basiron Y, Weng CK. The oil palm and its sustainability. J Oil Palm Res 2004;16(1):1–10.
[75] Ji CM, Eong PP, Ti TB, Seng CE, Ling CK. Biogas from palm oil effluent (POME): opportunities and challenges from Malaysia's perspective. Renew Sustain Energy Rev 2013;26:717–26.
[76] Umar MS, Jennings P, Urmee T. Strengthening the palm oil biomass renewable energy industry in Malaysia. Renew Energy 2013;60:107–15.
[77] Silalertruksa T, Gheewala SH. Environmental sustainability assessment of palm biodiesel production in Thailand. Energy 2012;43(1):306–14.
[78] Ong HC, Mahlia TMI, Masjuki RS, Norhasyima RS. Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: a review. Renew Sustain Energy Rev 2011;15(8):3501–15.
[79] Sulaiman F, Abdullah N, Gerhauser H, Shariff A. An outlook of Malaysian Energy, oil palm industry and its utilization of wastes as useful resources. Biomass Bioenergy 2011;35(9):3775–86.
[80] de Araújo CDM, de Andrade CC, Silva ES, Dupas FA. Biodiesel production from used cooking oil: a review. Renew Sustain Energy Rev 2013;27:445–52.
[81] ISO. International Standards Organisation. Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14040, Geneva, Switzerland.
[82] ISO. International Standards Organisation. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO 14044, Geneva, Switzerland.
[83] Chiaramonti D, Recchia L. Is life cycle assessment (LCA) a suitable method for quantitative CO_2 saving estimations? the impact of field input on the LCA results for a pure vegetable oil chain Biomass Bioenergy 2010;34(5):787–97.
[84] Carvalho A, Mimoso AF, Mendes AN, Matos HA. From a literature review to a framework for environmental process impact assessment index. J Clean Prod 2014;64:36–62.
[85] Lora EES, Escobar JCP, Rocha MH, Renó MLG, Venturini OJ, Almazán O. Issues to consider, existing tools and constraints in biofuels sustainability assessments. Energy 2011;36(4):2097–110.
[86] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S. Recent developments in life cycle assessment. J Environ Manage 2009;91(1):1–21.
[87] Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life cycle assessment Part 1: framework, goal and scope definition, inventory analysis, and applications. Environ Int 2004;30(5):701–20.
[88] Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, et al. Indirect emissions from biofuels: how important? Science 2009;326 (5958):1397–9.
[89] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319(5867):1235–8.
[90] Russi D. An integral assessment of a large-scale biodiesel production in Italy: killing several birds with one stone. Energy Policy 2008;36(3):1169–80.
[91] Scharlemann JPW, Laurance WF. How green are biofuels? Science 2008;319 (5859):43–4.
[92] Nelson JP, Kennedy PE. The use (and Abuse) of meta-analysis in environmental and natural resource economics: an assessment. Environ Resour Econ 2009;42(3):345–77.
[93] Capaz RS. Estudo do desempenho energético da produção de biocombustíveis: Aspectos metodológicos e estudo de caso (Study of the energy performance of biofuels production: Methodological aspects and case study). Dissertação de Mestrado em Engenharia da Energia (Master Thesis in Energy Engeneering). Universidade Federal de Itajubá (Federal University of Itajubá). Itajubá; 2009. 120p. [in portuguese].
[94] Macedo IC, Leal MRLV, Ramos da Silva, JEA. Balanço das emissões de gases de efeito estufa na produção e no uso do etanol no Brasil (Greenhouse gases emissions balance of the ethanol production and use in Brazil). Governo do Estado de São Paulo (São Paulo State Government). Secretaria do Meio Ambiente (Environmental Department), São Paulo; 2004. 37p. [in portuguese].
[95] Cavalett O, Ortega E. Integrated environmental assessment of biodiesel production from soybean in Brazil. J Clean Prod 2010;18(1):55–70.
[96] Tsoutsos T, Kouloumpis V, Zafiris T, Foteinis S. Life cycle assessment for biodiesel production under Greek climate conditions. J Clean Prod 2010;18 (4):328–35.
[97] Pradhan A, Shrestha DS, McAloon A, Yee W, Haas M, Duffield JA, et al. Energy life-cycle assessment of soybean biodiesel. United States Department of Agriculture (USDA). Agricultural Economic report Number 845; 2009. 25p.
[98] Carraretto C, Macor A, Mirandola A, Stoppato A, Tonon S. Biodiesel as alternative fuel: experimental analysis and energetic evaluations. Energy 2004;29(12–15):2195–211.
[99] Costa, RE. Inventário do Ciclo de Vida do Biodiesel obtido para as condições do Brasil e da Colômbia (Life Cycle Inventory of Biodiesel Obtained for the Brazilian and Colombian Conditions). Dissertação de Mestrado em Engenharia da Energia (Master Thesis in Energy Engeneering). Universidade Federal de Itajubá (Federal University of Itajubá). Itajubá; 2007. 267p. [in portuguese].
[100] Kamahara H, Hasanudin U, Widiyanto A, Tachibana R, Atsuta Y, Goto N, et al. Improvement potential for net energy balance of biodiesel derived from palm oil: a case study from Indonesian practice. Biomass Bioenergy 2010;34 (12):1818–24.
[101] Papong S, Chom-In T, Noksa-nga S, Malakul P. Life cycle energy efficiency and potentials of biodiesel production from palm oil in Thailand. Energy Policy 2010;38(1):226–33.
[102] Souza SP, Pacca S, Ávila MT, Borges JLB. Greenhouse gas emissions and energy balance of palm oil biofuel. Renew Energy 2010;35(11):2552–61.
[103] Pleanjai S, Gheewala SH. Full chain energy analysis of biodiesel production from palm oil in Thailand. Appl Energy 2009;86(Supplement 1):S209–14.
[104] Borges FJ. Inventário do ciclo de vida do PVC produzido no Brasil (Life cycle inventory of PVC made in Brazil). Dissertação de Mestrado em Engenharia Química (Master Thesis in Chemical Engineering). Escola Politécnica da Universidade de São Paulo (Polytechnic School of São Paulo University). São Paulo; 2004. 174p. [in portuguese].
[105] Ribeiro PH. Contribuição ao banco de dados brasileiro para apoio à avaliação do ciclo de vida: fertilizantes nitrogenados (Contribution to the Brazilian database to support the life cycle assessment: nitrogen fertilizers). Tese de Doutorado em Engenharia Química (Ph.D. Thesis in Chemical Engineering). Escola Politécnica da Universidade de São Paulo (Polytechnic School of São Paulo University). São Paulo; 2009. 375p. [in portuguese].
[106] Viana MM. Inventário do ciclo de vida do biodiesel etílico do óleo de girassol (Life cycle inventory of sunflower ethylic biodiesel). Dissertação de Mestrado em Engenharia Química (Master Thesis in Chemical Engineering). Escola Politécnica da Universidade de São Paulo (Polytechnic School of São Paulo University). São Paulo; 2008. 237p. [in portuguese].
[107] Coltro L, Garcia EEC, Queiroz GC. Life cycle inventory for electric energy system in Brazil. Int J Life Cycle Assess 2003;8(5):290–6.
[108] Camargo AM. Inventário do ciclo de vida do metanol para as condições brasileiras (Life cycle inventory of methanol to Brazilian conditions). Dissertação de Mestrado em Engenharia Química (Master Thesis in Chemical Engineering). Escola Politécnica da Universidade de São Paulo (Polytechnic School of São Paulo University). São Paulo; 2007. 132p. [in portuguese].
[109] Kulay LA. Uso da análise do ciclo de vida para a comparação do desempenho ambiental das rotas úmida e térmica de produção de fertilizantes fosfatados (Using the life cycle assessment for the comparison of the environmental performance of wet and thermal routes for production of phosphatic fertilizers). Tese de Doutorado em Engenharia Química (Ph.D. Thesis in Chemical Engineering). Escola Politécnica da Universidade de São Paulo (Polytechnic School of São Paulo University). São Paulo; 2004. 313p. [in portuguese].
[110] Althaus H-J, Chudacoff M, Hischier R, Jungbluth, N, Osses M, Primas A. Life cycle inventories of chemicals. Ecoinvent report, V2.0, no 8. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf; 2007.
[111] Classen M, Althaus H-J, Blaser S, Scharnhorst W, Tuchschmid M, Jungbluth N, et al. Life cycle inventories of metals. Final report Ecoinvent data, v2.0, no 10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf 2007.
[112] Frischknecht R, Jungbluth N. Database manual: The ETH-ESU 96 library. Netherlands: Simapro:Pré Consultants and ESU-services; 2001.
[113] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, et al. Life cycle assessment. an operational guide to the ISO standards. Leiden, The Netherlands: Center of Environmental Science, Leiden University (CML); 2001.
[114] Fore SR, Porter P, Lazarus W. Net energy balance of small-scale on-farm biodiesel production from canola and soybean. Biomass Bioenergy 2011;35 (5):2234–44.
[115] Kaltschmitt M, Reinhardt GA, Stelzer T. Life cycle analysis of biofuels under different environmental aspects. Biomass Bioenergy 1997;12(2):121–34.
[116] Frischknecht R, Althaus H-J, Bauer C, Doka G, Heck T, Jungbluth N, et al. The environmental relevance of capital goods in life cycle assessments of products and services. Int J Life Cycle Assess 2007;12(2):7–17.
[117] Guerra JPM, Coleta Jr. JR, Arruda LCM, Silva GA, Kulay L. Comparative analysis of electricity cogeneration in sugarcane production by LCA. Int J Life Cycle Assess 2014;19(4):814–25.

[118] Chahan MK, Varun, Chaudhary S, Kumar S, Samar. Life cycle assessment of sugar industry: a review. Renew Sustain Energy Rev 2011;15(7):3445–53.
[119] García CA, Fuentes A, Hennecke A, Riegelhaupt E, Manzini F, Masera O. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Appl Energy 2011;88(6):2088–97.
[120] Seabra JEA, Macedo IC. Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. Energy Policy 2011;39(1):421–8.
[121] Biswas WK, Barton L, Carter D. Biodiesel production in a semiarid environment: a life cycle assessment approach. Environ Sci Technol 2011;45 (7):3069–74.
[122] Moser BR. Biodiesel production, properties, and feedstocks. in vitro Cell Dev Biol – Plant 2009;45(3):229–66.
[123] Panichelli L, Dauriat A, Gnansounou E. Life cycle assessment of soybean-based biodiesel in Argentina for export. Int J Life Cycle Assess 2009;14 (2):144–59.
[124] Ramos LP, Wilhelm M. Current status of biodiesel development in Brazil. Appl Biochem Biotechnol 2005;123(1–3):807–19.
[125] Manik Y, Halog A. A meta-analytic review of life cycle assessment and flow analyses studies of palm oil biodiesel. Integr Environ Assess Manag 2013;9 (1):134–41.
[126] Pehnelt G, Vietze C. Recalculating GHG emissions saving of palm oil biodiesel. Environ, Dev Sustain 2013;15(2):429–79.
[127] Harsono SS, Prochnow A, Hansen A, Hallmann C. Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia. GCB Bioenergy 2012;4(2):213–28.
[128] Achten WMJ, Vandenbempt P, Almeida J, Mathijs E, Muys B. Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon. Environ Sci Technol 2010;44(12):4809–15.
[129] Arrieta FRP, Teixeira FN, Yáñez EEA, Lora EES, Castillo EE. Cogeneration potential in the Columbian palm oil industry: three case studies. Biomass Bioenergy 2007;31(7):503–11.
[130] Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. National Renewable Energy Laboratory (NREL). Final Report NREL/SR-580-24089; 1998. 314p.
[131] Luo L, van der Voet E, Huppes G. Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. Renew Sustain Energy Rev 2009;13 (6–7):1613–9.
[132] Cavalett O, Chagas MF, Seabra JEA, Bonomi A. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. Int J Life Cycle Assess 2013;18(3):647–58.
[133] Hellweg S, Geisler G. Life cycle impact assessment of pesticides: when active substances are spread into the environment. Int J Life Cycle Assess 2003;8 (5):310–2.
[134] Hou J, Zhang P, Yuan X, Zheng Y. Life cycle assessment of biodiesel from soybean, jatropha and microalgae in china conditions. Renew Sustain Energy Rev 2011;15(9):5081–91.
[135] Silalertruksa T, Gheewala SH. Environmental sustainability assessment of palm biodiesel production in Thailand. Energy 2012;43(1):306–14.
[136] Boddey RM, Soares LHB, Alves BJR, Urquiaga S. Bio-ethanol production in Brazil. In: Pimentel D, editor. Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks. Dordrecht (The Netherlands): Springer-Verlag; 2008. p. 320–56.
[137] Seabra JEA. Avaliação técnico-econômica de opções para o aproveitamento integral da biomassa de cana no Brasil (Technical-economic evaluation of options for whole use of sugarcane biomass in Brazil). Tese de Doutorado em Engenharia Mecânica (Ph.D. Thesis in Mechanical Engineering). Universidade Estadual de Campinas (Campinas State University), Campinas; 2008. 244p. [in portuguese].
[138] Coelho ST, Goldemberg J, Lucon O, Guardabassi P. Brazilian sugarcane ethanol: lesson learned. Energy Sustain Dev 2006;10(2):26–39.
[139] Oliveira MED, Vaughan BE, Rykiel Jr. E. Ethanol as fuel: energy carbon dioxide balances, and ecological footprint. BioScience 2005;55(7):593–602.
[140] Pimentel D, Patzek TW. Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. Nat Resour Res 2005;14(1):65–76.
[141] Nogueira LAH. Análise da utilização de energia na produção de álcool de cana-de-açúcar (Analysis of energy use in ethanol production from sugarcane). Tese de Doutorado em Engenharia Mecânica (Ph.D. Thesis in Mechanical Engineering). Faculdade de Engenharia Mecânica (Faculty of Mechanical Engineering). Universidade Estadual de Campinas (Campinas State University), Campinas; 1987. 164p. [in portuguese].
[142] BNDES. Brazilian Development Bank. Center for Strategic Studies and Management in Science, Technology and Innovation (CGEE). Sugarcane-Based Bioethanol: Energy for Sustainable Development. 1st ed. BNDES-CGEE:Rio de Janeiro; 2008. 304p.
[143] Galdos M, Cavalett O, Seabra JEA, Nogueira LAH, Bonomi A. Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions. Appl Energy 2013;104:576–82.
[144] Leal MRLV, Nogueira LAH, Cortez LAB. Land demand for ethanol production. Appl Energy 2013;102:266–71.
[145] Souza SP, Seabra JEA. Environmental benefits of the integrated production of ethanol and biodiesel. Appl Energy 2013;102:5–12.
[146] Salomon KR, Lora EES, Rocha MH, Almazán OO. Cost calculations for biogas from vinasse biodigestion and its energy utilization. Zuckerind (Sugar Ind) 2011;136(4):217–23.
[147] Ferrari RA, Oliveira VS, Scabio A. Biodiesel de Soja – Taxa de conversão em ésteres etílicos, caracterização físico-química e consumo em gerador de energia (Soybean biodiesel – Conversion rate in ethyl esters, physicochemical characterization and consumption in Power generator). Química Nova (New Chemistry); 28(1):19–23, 2005 [in portuguese].